Modelling and solar PV contribution to marine electric propulsion

by

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Declaration of Originality

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Paper 2: The dawning of the age of high-efficiency vessels

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Abstract

Efficiency improvement and emissions reduction initiatives world-wide are creating a significant opportunity for Australian shipbuilders. However, the application of electrical and renewable-energy technologies in vessels built by Australian aluminium shipbuilders is at least five years behind their European counterparts.

This research project reviewed international progress in marine electrical and renewable energy systems research and development. It also identified and highlighted the market drivers for high-efficiency vessel development in Australia.

A software model for use in the preliminary design of marine electric propulsion systems was investigated. The model development was commenced with an investigation of methods for approximating hull and propeller performance using minimal input parameters. The model was checked using the performance of the first all-electric ferry to operate on the Swan River in Perth, Western Australia.

The application of solar photovoltaic (PV) technology to marine propulsion was investigated. An index was developed for calculating a vessel's maximum feasible power by solar PV (MFPS). A solar PV battery charger was designed for a shunting locomotive, along with a reference PV cell and data logging equipment. The use of a locomotive provided a moving platform with some similarities to a shipboard solar PV installation, but with the benefit of continuous operation within 3.5km of two Bureau of Meteorology weather stations. Analysis of the weather and insolation data sets provides insights for improving the design of future marine solar PV installations.

Chapter 1: Introduction

1.1 Background

Marine electric propulsion has a long history in diesel-electric propulsion for submarines, warships, cruise ships and ice-breakers. In the past decade, development of electric propulsion for small recreational vessels, ferries and combat ships has accelerated. Some novel and effective electric vessels built recently include:

- "MS Turanor PlanetSolar" all-electric solar vessel, which completed the first solar-powered global circumnavigation.[1]
- "Ar Vag Tredan" all-electric supercapacitor ferry operating in France.[2, 3]
- "Ampere" all-electric, lithium-ion battery ferry operating in Norway.[4]
- "Future of the Fjords" all-electric, lithium-ion battery ferry operating in Norway.[5]
- "Ellie J" all-electric, lithium-ion battery ferry operating in Australia.[6]
- "Kato" sail and electric hybrid cruising catamaran operating in Australia.[7]

However, there has been little effort so far in taking learnings from these novel new-builds and applying the new technologies in a more systematic and cost-effective manner when compared to, for example, the considerable development occurring in the electric vehicle industry.[8, 9] For these reasons, as a first step in this project, an extensive literature review of emerging technologies for vessel and vehicle electric propulsion was completed and this was published in a journal paper titled, "Emerging technologies in marine electric propulsion". [10] The journal paper was peer-reviewed and first published in 2014 and is incorporated in Chapter 2, section 2.2 of this thesis. Changes in the technologies since 2014 are included as an epilogue in section 2.3.

1.2 Motivation

The market for lightweight, aluminium vessels is dominated by Australian shipbuilders.[11] Based on industry discussions and ideas formed from the literature review[10], technology comparison, scaling and optimization of electrical systems and solar PV system design for small and mid-sized vessels, were found worthwhile for particular focus in the Australian context.

It was identified that there is a window of opportunity for Australian shipbuilders to enter the electric vessel market. There is awareness by Australian shipbuilders of the increasing interest from European vessel operators in electric propulsion and the acceleration of electric vessel development world-wide. However the system-level understanding required to design and competitively build vessels at a scale and at a pace to meet future demand is still nascent. This window of opportunity was explored and the decision made to highlight the issues to Australian industry, governments, and researchers by publishing the journal paper, "The dawning of the age of high-efficiency vessels" [12]. The journal paper was peer-reviewed and first published in 2015 and is incorporated in Chapter 3, section 3.2 of this thesis. Developments in electric propulsion in Australia since 2015 are included as an epilogue in section 3.3.

1.3 Objectives

From this early work was developed the research question: "What are the combinations of heat engine, fuel cell, solar PV, energy storage and electric propulsion that are best suited for providing optimum efficiency and adequate propulsive power in vessels with river and island ferry operational profiles (12m to 50m)?" This prompted a plan early in the project to develop, or contribute towards development of, a software model to answer the research question.

The project commenced with the search for a suitable methodology for hull resistance and propeller powering estimation that could be applied to the preliminary stage of vessel design. Previous work by Moody[13] fit the requirements and appeared readily adaptable to a model for electric vessel propulsion. In parallel with this, a search for suitable modelling software determined that Matlab and Simscape modules might be readily adapted to a marine electric propulsion model. The adaption of Moody's methodology and development of his model for use with electric propulsion is explained in Chapter 4, section 4.1.

By engaging with marine industry participants at the forefront of marine electric propulsion development in Australia, the author was presented with several unique opportunities during the project. One of these was the launch of the first all-electric river ferry in Australia, the "Ellie J". An explanation of the significance of this vessel was first published in the IEEE Transportation Electrification Community's July 2017 newsletter[6] and this article is incorporated in Chapter 4, section 4.2. The article also highlights the importance of recent developments in marine electric propulsion. The "Ellie J" was an ideal test case for the hull resistance and powering performance model, as detailed in Appendix A.

The next area of focus in development of a marine electric propulsion model was solar photovoltaic (PV) performance and design. While silicon PV technology has been available commercially for more than three decades, understanding of its performance in marine vessel applications is limited. An improved understanding of the performance of solar PV technology is required in order to design effective systems, model the systems and increase its use. Chapter 5 introduces the novel concept of maximum feasible power by solar PV (MFPS), an index of the feasible contribution of solar PV energy to a vessel's propulsion.

Chapter 5 then describes the development of a prototype solar PV system in order to explore design factors and real-world energy yield of PV technology. Research into the marine application of solar PV technology would suggest using a developmental system installed on a ferry or a ship, however these systems are generally located away from land-based meteorology infrastructure. An established meteorology station, with accurate weather and solar energy (insolation) measurements, would enable a nearby PV system to be compared against a verifiable benchmark. A fixed PV system on land would tie the system to the conditions of the installation site. The opportunity arose during the project to design and install a solar PV system on a shunting locomotive, believed to be the first installation of its kind in Australia. The system includes a solar PV reference cell and data logging equipment. The locomotive operates in close proximity to two Bureau of Meteorology (BOM) weather stations. This enabled calibration against high quality insolation and weather data and analysis of a system on a moving platform. The finding will be relevant to the design of future marine vessel solar PV systems.

Chapter 2: Literature Review

Part of the research contained within this chapter has been published as William P Symington, Alan Belle, Hung D Nguyen and Jonathan R Binns, Emerging technologies in marine electric propulsion, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, Volume: 230 issue: 1, page(s): 187-198, 2014.

2.1 Overview of Chapter 2

The first step in this project was an extensive literature review of emerging technologies for vessel and vehicle electric propulsion. The technologies were grouped and categorised in terms of technology maturity, in order to identify gaps and opportunities. On completion of the literature review it was considered that publication of the findings as a review paper would be useful for increasing awareness among marine engineering designers and researchers of the opportunities for development and application of Marine Electric Propulsion (MEP) technologies. Section 2.2 of this chapter is a copy of the paper published in Dec 2014.

Section 2.3 of this chapter provides an epilogue to the published paper and evaluates some of the conclusions based on technology developments between 2014 and 2018.

Section 2.4 reviews literature relating to modelling of Marine Electric Propulsion systems, which was an important consideration in the early stages of the research project.

2.2 Emerging technologies in marine electric propulsion

2.2.1 Abstract

Increasing fuel costs and regulation of emissions are encouraging operators, shipbuilders and researchers to seek improvements in marine vessel efficiency. In the area of vessel electrical systems, there are increasing choices as a result of research and development over the past decade, giving rise to a number of promising new technologies. Promising new battery chemistries are being developed and existing chemistries are being enhanced with nano-technology. Supercapacitors and fuel cells are now powering ferries. Permanent magnets are enabling novel motor topologies and solar panel prices are decreasing. In addition to new technologies recently commercialised for vessels, new developments in electric vehicles and grid electrical systems will be applicable to the marine environment. This article reviews emerging electrical technologies and it focusses on those with potential for improving vessel efficiency within the next decade.

2.2.2 Introduction

The 62nd session of the International Maritime Organisation (IMO) Marine Environment Protection Committee (MEPC) introduced mandatory measures, including the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships, in order to accelerate efficiency improvements and reduce emissions. Vessel designers are faced with many choices in meeting these new measures, not least in electrical technologies.

Electric propulsion is not a new concept. It has been used since the early 20th century, mainly in diesel-electric propulsion systems in submarines, warships, cruise ships and ice-breakers.[14] In the 21st century the use of electric propulsion is increasing for various reasons,[15] such as facilitation of:

- More flexible machinery arrangements;
- Low noise operation;
- Improved vessel efficiency when partially loaded or with large auxiliary loads;
- Increased manoeuvrability, for example via pod propulsors;
- Increased systems redundancy;
- Use of solar energy and fuel cells.

Recent notable applications of electric propulsion in ships include the PlanetSolar solar-powered circumnavigation, Oasis class cruise ships, the Solar Albatross ferry, the Ar Vag Tredan supercapacitor ferry and the FCS Alsterwasser fuel cell ferry.[1, 2, 16-18]

Electrical systems are playing an increasingly important role in vessel efficiency in the following areas:

- Energy sources, such as shore electrical supply and alternators;
- Rechargeable energy storage systems (ESS), such as batteries and supercapacitors;
- Electric motors used in main propulsion drives and tunnel thrusters;
- Power management systems for vessel propulsion and electrical auxiliary power.

This article examines emerging electrical technologies and their applications, with potential to provide further improvements in commercial vessel efficiency.

2.2.3 On-board electricity generation

The efficiency of on-board electricity generation is important in all vessels. In recent decades there has been considerable research into improved generation efficiency and the use of renewable energy sources. Included in these efforts has been research into application of nuclear, wave, wind, solar and gas technologies for marine vessels. In keeping with a focus on electricity generation improvements likely to be commercially feasible within a decade, we review electricity generation via solar and gas fuel cells.

An important feature of renewable energies such as solar and wind is that the fuel is free. Direct conversion of wind kinetic energy to vessel kinetic energy by sails and kites has great potential for renewable energy propulsion;[19] however it is beyond the scope of this article. On-board wind generation of electricity is used on cruising yachts[20] and has potential for electricity generation on other stationary vessels.

2.2.4 Solar energy

Solar energy is proving increasingly viable for on-board electricity generation. There are, however, limitations to the practical application of solar energy to vessels. Solar energy yield is limited by the vessel's solar energy collection area and the peak solar irradiance available at noon in clear weather, of around 1 kW/m^2.[21] A vessel's solar energy collection area varies with the solar angle of incidence and is limited by available topside and competing superstructure requirements. Solar Sailor Holdings Ltd[17] has improved solar energy collection area by incorporating solar cells on wing sails.

Solar energy can be converted directly into electricity with solar photovoltaic (PV) cells, or into heat energy using solar thermal collectors. Solar water heating by means of thermal collectors is a mature technology and is viable for water heating for on-board hotel services.

Concentrating reflective solar thermal technology is unlikely to be competitive with solar PV for electricity generation aboard marine vessels. Practical problems conspiring against its adaptation to the marine environment include the following:

1. Constant vessel movement and vessel flexing will compound problems of mirror focussing accuracy.
2. Salt encrustation on a concentrating receiver lens is likely to rapidly degrade system efficiency.

For these reasons PV will remain the leading solar energy conversion technology for marine vessels in the near term.

Solar PV systems. These have been used to convert solar irradiance directly into electrical energy on recreational sailing vessels for more than two decades. Significant efficiency improvements and cost reductions have brought PV panels to the point where they have been used for marine propulsion energy by the Solar Sailor ferry launched in 1999[17] and the first circumnavigation under solar power by the PlanetSolar vessel in 2012.[1]

Figure 1 shows that commercial solar PV cell efficiencies have improved almost linearly for more than a decade.

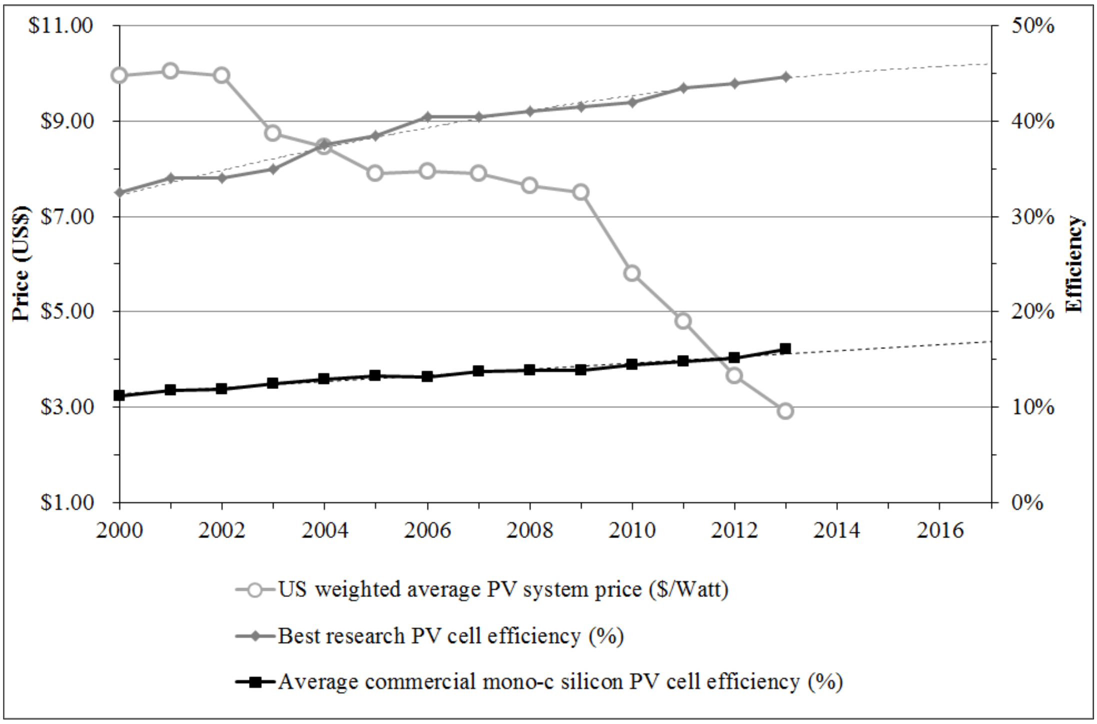

Figure 1. Solar PV efficiency and price, 2000 to 2013.[22-24]

The average efficiency of commercially-produced, mono-crystalline, silicon PV cells increased from 11% to 16% between 2000 and 2013.[22] Over the same period, the best research cell efficiencies improved from 32.5% to 44.7%.[23] The best research cells achieve efficiencies higher than the Shockley-Queisser limit for silicon p-n junctions (29%) by layering several technologies, enabling an increasing proportion of the solar spectrum - from infrared (IR) to ultra-violet (UV) - to be used. Some tapering of research cell efficiency gains is apparent in the fitted trend curve (see Figure 1), as technologies approach 50% efficiency. The difference in 2013 between average commercial cell efficiency (16%) and best research cell efficiency (44.7%) suggests that opportunities for ongoing improvements in commercial cell efficiencies remain. Figure 2 indicates where the opportunities might lie and extensive details can be found in a report by the Science, Technology and Applications Group of the EU Photovoltaic Technology Platform.[25]

The US weighted average price of installed land-based PV systems has decreased significantly, from around US$10 per Watt in 2000 to less than US$3 per Watt in 2013, primarily attributable to reductions in PV module costs.[24] Solar PV system prices are likely to continue the downward trend for at least the next decade, due to increasing global production capacity, manufacturing improvements, ongoing cell efficiency improvements and commercialisation of lower-cost technologies.

Technology maturity is an important design consideration in ensuring reliability, availability, maintainability and safety of a system. Technology maturity can be classified as follows;

1. Mature Technology: Technology that has been in commercial use for more than 10 years and is available from many manufacturers.
2. Commercial: Recently commercialised technology, which has been available for less than 10 years and is generally only available from a small number of manufacturers.
3. Developmental: Technology still under development, that is not generally available as a commercial product.

Figure 2 shows solar PV technology types and their technology maturity.

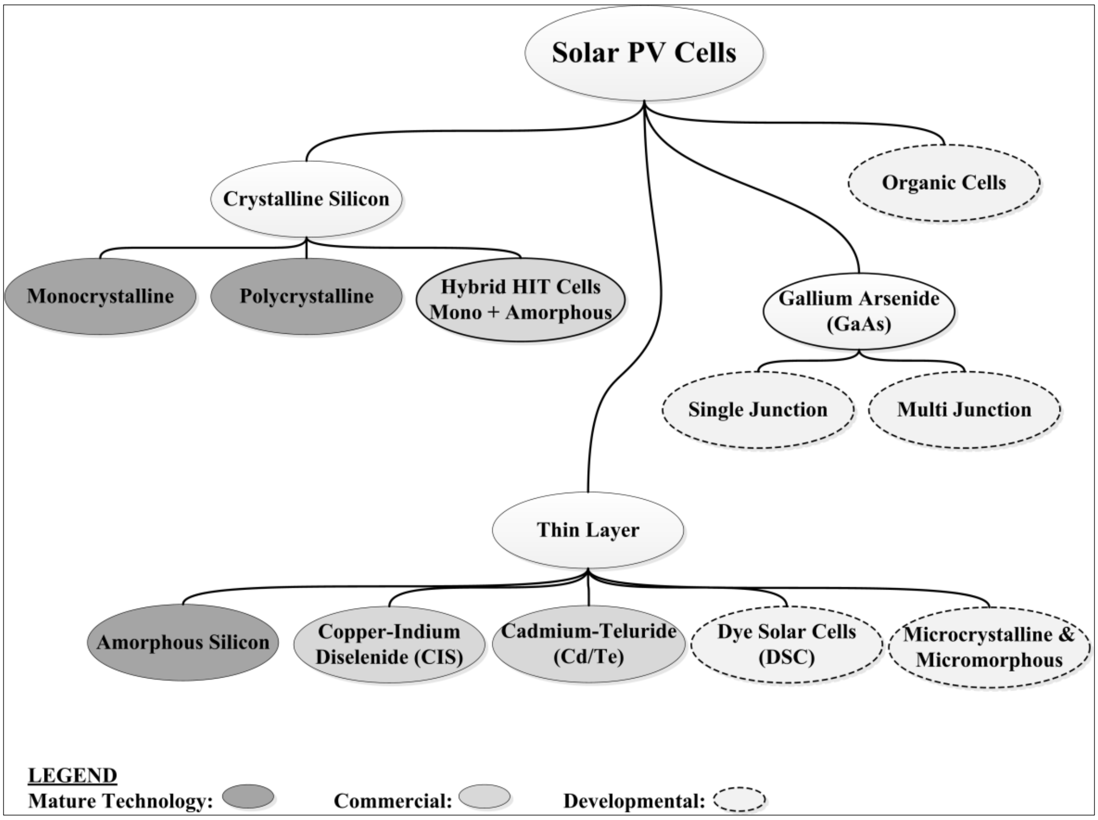

Figure 2. Solar PV technologies. Technology maturity is indicated by grey scale. [21, 23]

Mature solar PV technologies such as mono-crystalline and multi-crystalline silicon panels are inexpensive and readily available for use on vessels. Thin layer amorphous silicon cells are currently more expensive, but can be used on curved surfaces. Solid state dye solar cells[26] are showing promise with regard to further reduction of PV production costs. For example, Tata Steel Europe and Dyesol Ltd have demonstrated the production of dye solar cells on coil rolled steel roofing panels.

Due to the high variability of solar irradiance, on-board energy storage is required to store energy during supply peaks for later use during load peaks. In hybrid applications, energy storage supplemented by solar energy can provide fuel savings in diesel-electric vessels, by enabling installation of a smaller diesel engine, or operating the engine at its most efficient speed and load. In the case of sailing vessels, solar energy coupled with energy storage enables engines to be switched off when under sail.

It should be remembered in context that 1 kW/m^2 peak solar irradiance onto 18% efficient solar panels would generate a maximum of 9 kW from a 50 m^2 (10 m x 5 m) array on a 15 m length vessel, excluding any further system losses. Therefore solar PV panels can only provide auxiliary power or a small proportion of the propulsion power of a commercial vessel in continuous operation. Nevertheless, improving capital costs and free fuel improves the case for increased use of solar power for supplementing marine vessel power systems.

2.2.5 Fuel cells

Fuel cells convert chemical energy directly into electricity and have potential to be an alternative or supplementary technology to diesel engines coupled with alternators (gensets). The US Department of Energy[27] lists seven types of fuel cell technology, which are categorised in Figure 3.

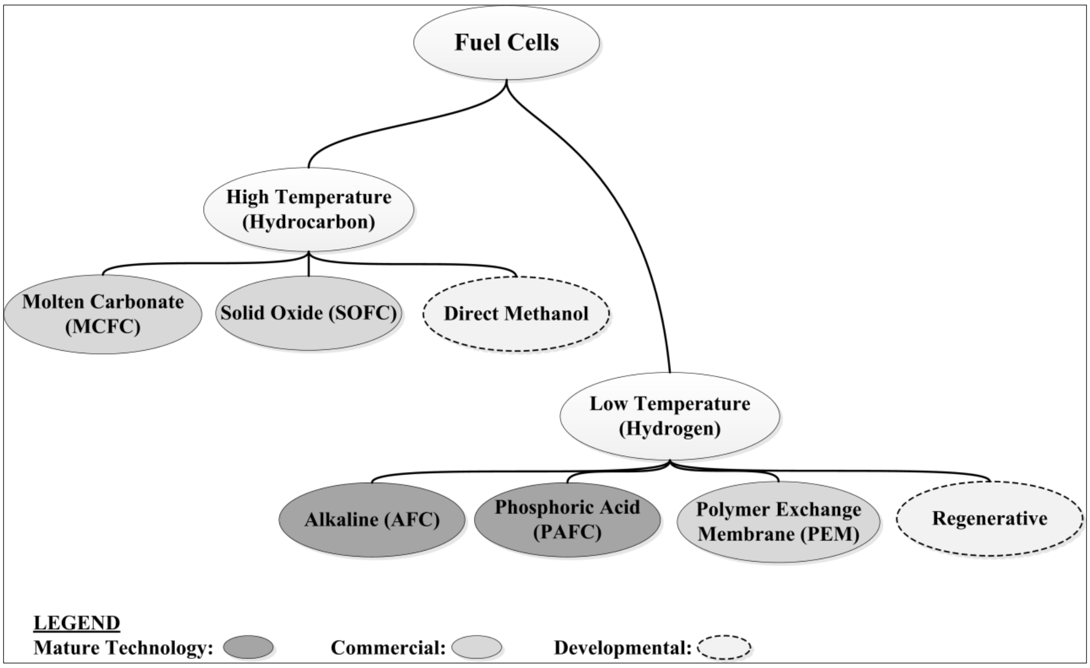

Figure 3. Fuel cell types and technology maturity. [27, 28]

Polymer exchange membrane (PEM) fuel cells are a focus of development in electric vehicles[8], and have been used to power German HDW submarines, MTU's 'No.1' yacht and the ferry FCS Alsterwasser.[29] The feasibility of hydrogen fuel cell technologies for wider use is dependent on hydrogen fuel distribution and storage. There remain significant technical challenges to be overcome in safely storing hydrogen at a comparable energy density to hydrocarbon fuels such as marine diesel oil (MDO) or liquid natural gas (LNG or liquid methane). Carlton et al.[28] suggest that solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) technologies, which are able to use hydrocarbon fuels, will be more promising for ship propulsion until hydrogen fuel infrastructure is more widespread and hydrogen fuel storage technologies are further developed.

The ability to use LNG will in the near term be an important advantage for high-temperature fuel cells compared to low-temperature fuel cells. The International Energy Agency (IEA) World Energy Outlook 2013 forecasts steady or decreasing prices for LNG between 2015 and 2025.[30] Concurrent with an improving LNG price advantage over MDO and heavy fuel oil, are the following:

- an improving LNG marine bunkering supply chain, particularly in Europe;[31]
- proposals to fuel propulsion with LNG to meet IMO MARPOL Annex VI requirements;[28, 31-33]
- established gas-powered technologies such as Miller cycle gas engines.[31]

These factors suggest that the use of LNG fuel for shipping will increase rapidly over the next decade. The supply chain is therefore being established to provide the LNG for use in high-temperature fuel cells.

Domestic SOFC systems are commercially available that use natural gas (CNG or methane) fuel and operate at around 700ºC to produce electricity, heat and CO_2. Electrical efficiencies of up to 60% and total system efficiencies of 85% with heat recovery have been claimed.[34] The Bluegen® SOFC units manufactured by Ceramic Fuel Cells Limited produce a continuous 1.5 kW of electricity from a unit the size of a washing machine. One unit would be capable of supplying auxiliary power and hot water for a small ferry, trawler or live-aboard work boat.

While SOFC fuel cells are now achieving higher efficiencies than gensets, there are two disadvantages at this stage of fuel cell development;

- Lower power density, as highlighted by DNV [18]. However, DNV did not include SOFC units in their comparison and it is unclear as to whether DNV's power density comparison included genset alternators, or engines alone.
- Higher capital cost.[18]

The use of LNG powered fuel cells to improve electrical generation efficiency on vessels equipped with LNG fuel storage would be a feasible step in the development of fuel cell technology for vessels.

2.2.6 Rechargeable energy storage

Rechargeable energy storage will enable increased use of shore electrical power and solar PV, as well as facilitating the running of engines and fuel cells constantly at their peak efficiency. A fundamental problem with existing electrical energy storage technologies is their significantly lower energy densities (up to 1.3 MJ/litre) compared with hydrocarbon fuels (up to 37 MJ/litre). Improvements are emerging and these will be examined further in the following sections.

2.2.7 Rechargeable batteries

Battery technologies are categorised by structure and technology maturity in Figure 4. Figure 5 compares key energy storage technologies in terms of specific energy (Wh/kg) and specific power (W/kg).

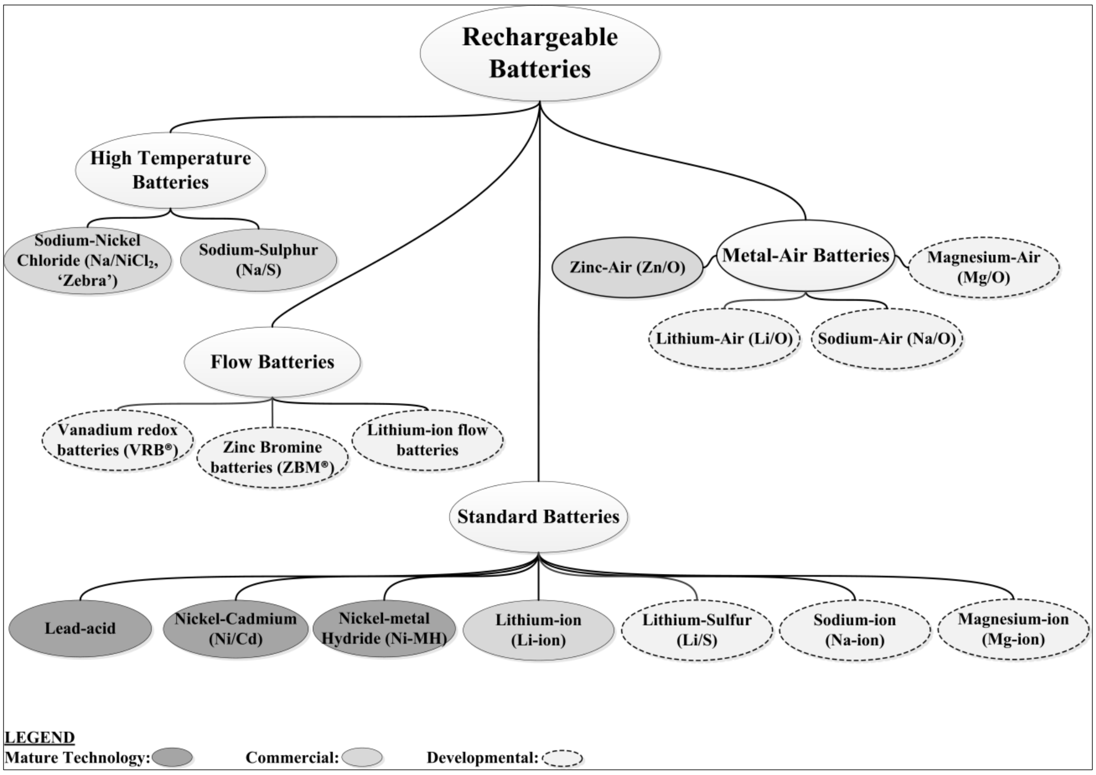

Figure 4. Battery types.[28, 35-38]

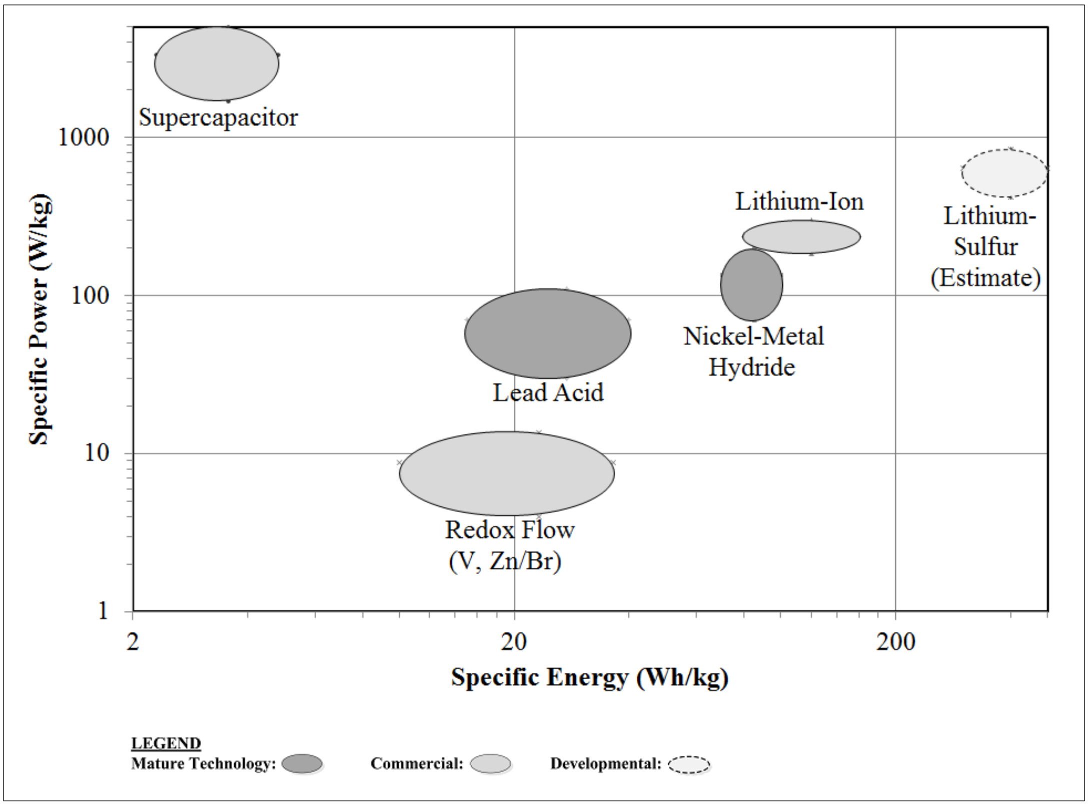

Figure 5. Specific energy and specific power comparison of energy storage technologies.[39-43] Technology maturity is indicated by greyscale.[28, 35-37] Crosses are data points for the Ragone plot.

Lead-acid batteries are a mature technology with a low capital cost. Disadvantages of lead-acid battery technology include;

- Low maximum current rating compared to newer technologies.
- Low specific energy (see Figure 5) and low energy density mean that lead-acid batteries are heavier and bulkier than newer technologies.

Nickel-metal hydride (NiMH) batteries are used in Toyota Prius and Honda Accord hybrid vehicles due to the energy density advantage over lead-acid batteries (see Figure 5).

Lithium-ion batteries are used in the Chevrolet Volt and Tesla electric vehicles and are expected to displace NiMH batteries in future hybrid and electric vehicles.[8] Lithium-ion batteries have been the subject of intensive research and development over the past decade because of their high specific performance. Problems with the technology, leading to battery fires in laptops, Boeing 787 Dreamliner aircraft and electric vehicles, have raised safety concerns. The risk of lithium-ion battery fires is being mitigated with newer chemistries, improved battery management systems, updated standards and more extensive testing.[36, 44]

In terms of high energy density and high power density, lithium-ion batteries are currently the leading commercial technology for vessel electrical energy storage and are commercially available for use with electric outboard motors and in large marine vessel installations.[45, 46]

An emerging problem with lithium-based technologies is the relative rarity and price of lithium.[28] Dunn et al[36] suggest sodium as a possible lower-cost alternative to lithium in ambient-temperature Na-ion cells and Carlton et al[28] suggest the use of magnesium. These alternatives are disadvantaged by their early stage of development, as well as the additional atomic mass of the elements when compared with lithium.

Flow batteries. Flow batteries utilise a pump to move electrolytes across electrodes, where reduction and oxidation occur, and then into storage tanks.[35] The capacity of flow batteries is dependent on the volume of electrolytes in storage.

As most of the energy in flow batteries is stored in the electrolyte tanks and away from the electrode system, they are inherently safer under short-circuit conditions than battery types where the full system energy is available at the electrodes.[35] Flow batteries therefore have a lower risk of explosion and fire, which may make them a safer option for bulk energy storage in ships. Development of flow batteries for grid-connected applications is leading to increased robustness of components such as storage tanks, electrode separator membranes and pumps.

A significant disadvantage of current technology flow batteries is their low specific energy and low specific power (see Figure 5). Dunn et al[36] suggest that the low specific energies of flow batteries might be improved by research combining the chemistries of lithium-ion batteries with the mechanics and principles of flow batteries in the form of lithium-ion redox flow batteries. The future viability of flow battery technology for use in ships will hinge on the success of these developments.

Metal-air & lithium-sulfur batteries. Until recently, it was considered that conventional battery chemistries were unlikely to be stable above 250 Wh/kg.[8] Carlton et al[28] suggest metal-air batteries as a possible path for improving battery energy density. These have an advantage compared to other types because the oxidant (air) is not included in the battery mass. There are considerable issues to resolve in manufacturing commercial lithium-air cells. As Dunn et al[36] explain, '…there is little doubt that rechargeable Li-air cells either for electric vehicles or grid storage applications still have a long research and development path.'

Recent developments in carbon nano-technologies applied to lithium-sulfur batteries have shown that these could exceed 300 W·h/kg.[39] Lithium-sulfur batteries are estimated to be 5 to 8 years away from commercialisation.[47] If lithium-sulfur performance estimates[39] can be achieved in commercial production of safe battery systems, then lithium-sulfur will be to lithium-ion what lithium-ion is to lead-acid (see Figure 5).

2.2.8 Supercapacitors or electric double-layer capacitors (EDLCs)

Rapid, high-power, ESSs such as supercapacitors, flywheels and superconducting magnetic energy storage (SMES) are suitable for vessels requiring rapid recharging and frequent, short bursts of power, such as tugs and river ferries.

Yichao and Khaligh[48] compare supercapacitors and flywheels and favour supercapacitors for marine applications due to lower standby losses, higher power density, faster recharge, higher stability and better safety. The ferry Ar Vag Tredan has demonstrated the feasibility of supercapacitors for use in electric propulsion.[49] Figure 5 shows the high specific power of commercially-available supercapacitors. Supercapacitors also have a very high cycle life (1 to 1.5 million cycles[40, 41]) when compared with batteries (1000 to 5000 cycles[43]). The combination of supercapacitors with lithium-ion batteries is recommended[50] for improving battery life, increasing power density and improving power response times of ESSs.

2.2.9 Electric propulsion motors

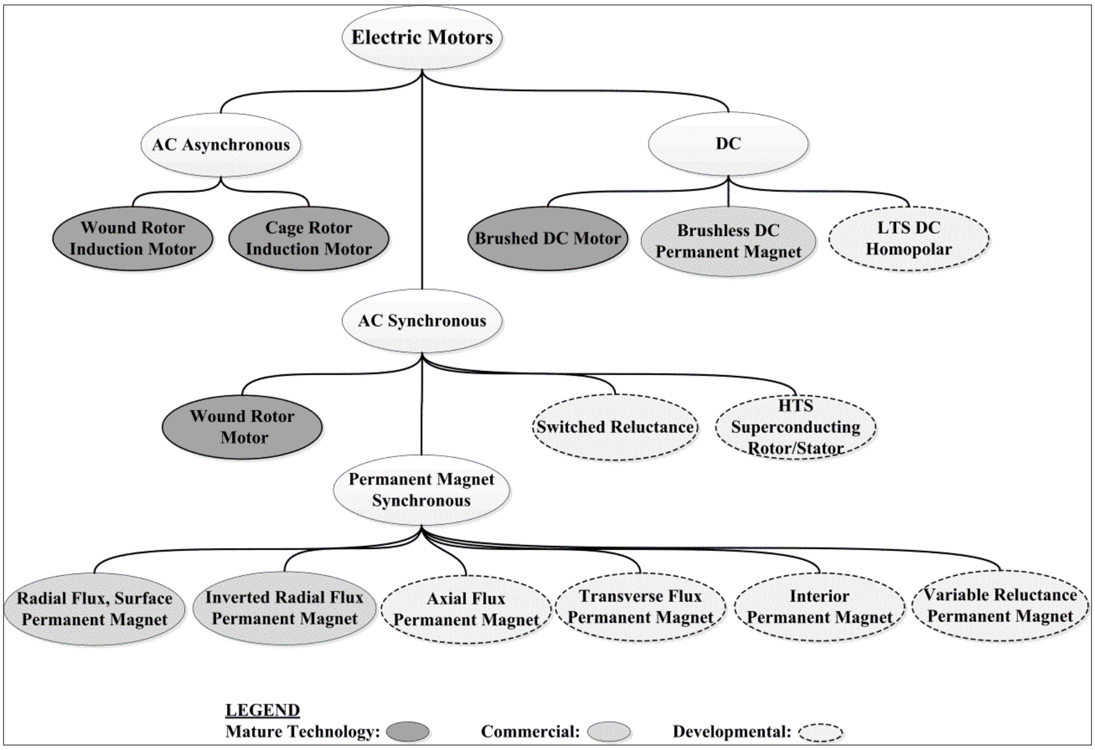

Figure 6. Electric motors by type and technology maturity. [8, 14, 51, 52]

Types and technology maturity of marine electric propulsion motors are shown in Figure 6. Miller[8] and Zhu and Howe[51] compare electric motor types for use in hybrid electric vehicles. Motors with brushes are inefficient and require regular servicing to maintain the brushes. Brushless DC motors (BDCM or BLDM) fitted with surface permanent magnets (SPMs) have high efficiency and high torque at low speed.[8] There are problems using BDCM at high rotor speeds and they are limited to around 5 MW.[14]

The four main competing AC brushless technologies used for traction in hybrid vehicles are:

a) Squirrel-cage induction motors (IM) with aluminium or copper cage rotors;
b) Interior permanent magnet (IPM) machines;
c) Surface permanent magnet (SPM) machines;
d) Switched reluctance machines (SRM).

Bench tests show that, of the first three motor types, surface permanent magnet machines have the lowest running temperature and lowest power factor, followed by interior permanent magnet machines and then induction motors.[8]

Induction motors have the lowest capital cost due to mature manufacturing processes and the absence of high cost, rare-earth elements used in permanent magnets.[52] Switched reluctance machine (SRM) technology has potential to provide comparable performance to permanent magnet motors and has a lower cost because it uses a steel rotor core without rare-earth elements.[53] SRMs are robust and their torque-speed curve can be tailored for the application, however prototypes exhibit high torque ripple, causing vibration and noise.[54]

Variable reluctance permanent magnet (VRPM) technology is relatively new. VRPM motors provide very high torque at low speed, although prototypes have high axial flux losses and the technology is not yet well understood.[54]

Electric outboard manufacturers such as Aqua Watt and Torqeedo have made significant progress recently in commercialising electric motors up to 60 kW. The DC motors used by Torqeedo in small electric outboard pod propulsors utilise permanent magnets in a novel bell rotor that rotates on the outside of the stator.[45] This inverted radial flux arrangement is claimed to provide more than double the torque of conventional radial flux rotor topologies.

Large ship propulsion system manufacturer ABB utilises permanent magnet synchronous motors in their ‘compact’ (1.3 MW to 4.5 MW) CO series pod propulsors.[55] Siemens manufactures mid-sized (5 MW to 12 MW) pod propulsors with a permanent magnet synchronous motor driving dual propellers.[56] Permanent magnet motors enable smaller motor diameters and smaller pod diameters which provide improved hydrodynamic efficiency, as well as improved motor efficiency.[14]

Siemens also manufactures 1 MW to 4 MW permanent magnet synchronous motors (‘SINAVY Permasyn’), which are used in Type 212 submarines in service with the German and Italian navies. The motor topology enabled by permanent magnets provides a shorter machine length with a claimed higher torque density compared to conventional radial flux topologies.

In rim-drive ducted propellers, permanent magnet electric motors are located around the circumference of the propeller,[54] rather than at the centre-line. This enables the elimination of shafts, gears and hubs. Schottel, Brunvoll and Voith Turbo have recently commercialised permanent magnet rim-drive propeller systems for use in bow thrusters and ducted propulsors. These represent another example of permanent magnets enabling novel motor topologies that could make electric propulsion a more attractive option.

2.2.10 High-temperature superconductors

High-temperature superconductors (HTS) are a class of ceramic materials that exhibit electron super-conduction at temperatures greater than 5 K (-268ºC). Second Generation HTS materials are super-conducting at temperatures as high as 77 K (-196 ºC), so that liquid nitrogen is a viable cryogenic coolant.[57]

Figure 7 compares efficiencies of a 5 MW high-temperature superconductor rotor motor versus a 56 kW surface permanent magnet motor and a 56 kW induction motor (EPACT energy efficient standard).

Efficiencies over 95% are being achieved with permanent magnet motors and Figure 7 shows that there is insufficient opportunity gap for high-temperature superconductor motors to provide significant improvements in motor efficiency. However, the very high power density of HTS wire has been shown experimentally to enable a reduction in motor size and mass to around 50% of conventional motors with a similar power rating.[58, 59] The smaller size of HTS motors potentially improves the motor placement options in larger vessels and the smaller mass may assist application in high-speed vessels.

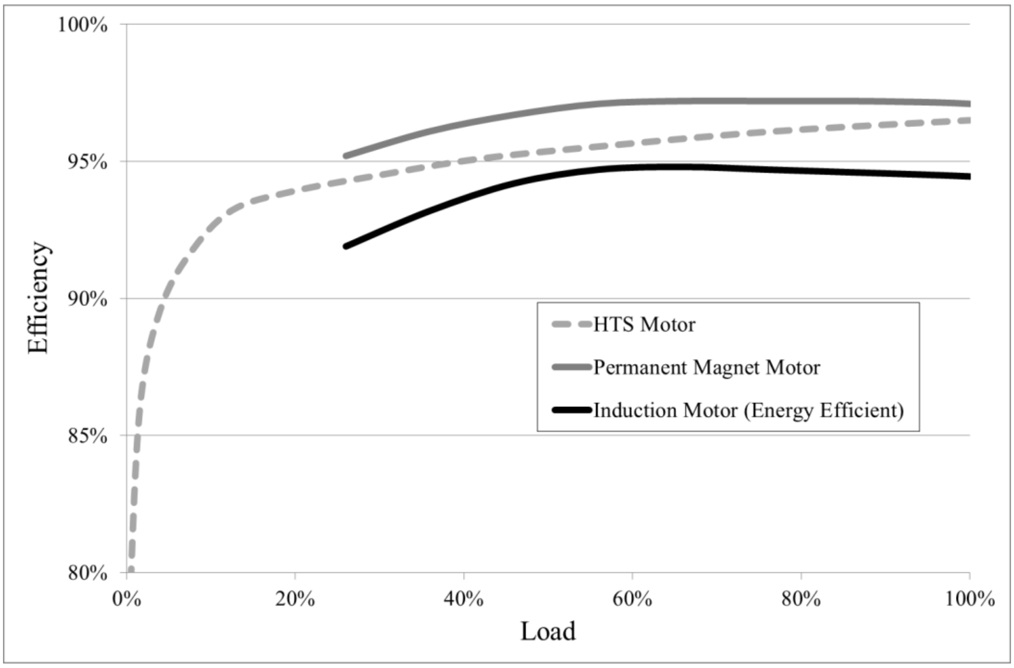

Figure 7. Efficiency comparison of motors. HTS data is from Eckels and Snitchler, Figure 3.[58] PM and IM data is from Melfi, Evon and McElveen , Figure 10(a).[52]

A disadvantage of high-temperature superconductor motors is the increased complexity due to the cryogenic cooling systems required to maintain the wire in a super-conducting state. Whilst the power consumption of a cryogenic cooling system is negligible for large HTS machines[59], the added complexity is a significant consideration. Ross et al[60] predict that diesel-HTS-electric drives will only be cost-effective compared to traditional diesel-electric drives in vessels with highly variable load and speed requirements, such as work ships, coastal freighters, patrol vessels and tugs.

A further disadvantage is the high cost of HTS wire due to its early stage of commercialisation. Ross et al[60] calculate that HTS wire prices will need to fall by a factor of six for HTS to be a viable alternative to copper-wound motors. Hazelton[57] forecasts that HTS wire prices will drop by a factor of seven between 2013 and 2017, from US$225 to US$30 per kAm. HTS price improvements are being driven by the use of HTS wire in applications such as magnetic resonance imaging (MRI) machines and particle accelerators. Combining the forecasts of Ross et al. and Hazelton raises the interesting possibility that high-temperature superconductor machines may be an economically viable option for niche applications by 2020.

2.2.11 High-power DC distribution

High-power DC distribution systems have been recommended for interfacing disparate voltages and frequencies, for example, in connecting high-speed alternators powered by gas turbines to low-speed electric motors.[61-63] DC power distribution is used in electric and hybrid vehicles, by Torqeedo in electric outboard systems and in the integrated electric propulsion of the destroyer USS Zumwalt. The Institute of Electrical and Electronic Engineers (IEEE) recently developed a power systems standard for Medium Voltage DC (MVDC, >1 kV) in ships.[62] The further application of high-power DC distribution has potential to facilitate power transfer between:

- High-frequency alternators;
- Low-speed propulsion motors;
- DC energy sources such as solar PV and fuel cells,
- DC energy storage such as batteries and supercapacitors;
- DC loads such as electronics systems and LED lighting.

Moreno and Pigazo[14] in 2007 suggested a possible future ship electrical system configuration. Based on recent developments, this could be updated to the system shown by the single-line diagram in Figure 8. A major change shown in Figure 8, from the system defined by Moreno and Pigazo, is that power electronics ratings have increased to the extent that they can now transform major power loads that previously could only be reliably performed with heavy and bulky transformers[63].

2.2.12 Power electronics

Power electronics devices used in the electrical converters and motor drives shown in Figure 8 consist of diodes, silicon controlled rectifiers (SCRs), gate turn off (GTO) thyristors and insulated gate bipolar transistors (IGBTs). Around 20% of the energy loss in hybrid petrol-electric vehicles occurs in the power semiconductors in the vehicle's power control unit (PCU). Toyota and Denso Corporation have developed silicon carbide (SiC) power semiconductor devices for hybrid vehicles, which are claimed to reduce semiconductor energy loss, enabling a reduction in PCU size by approximately 80% and a hybrid vehicle fuel efficiency improvement exceeding 5%.[64]

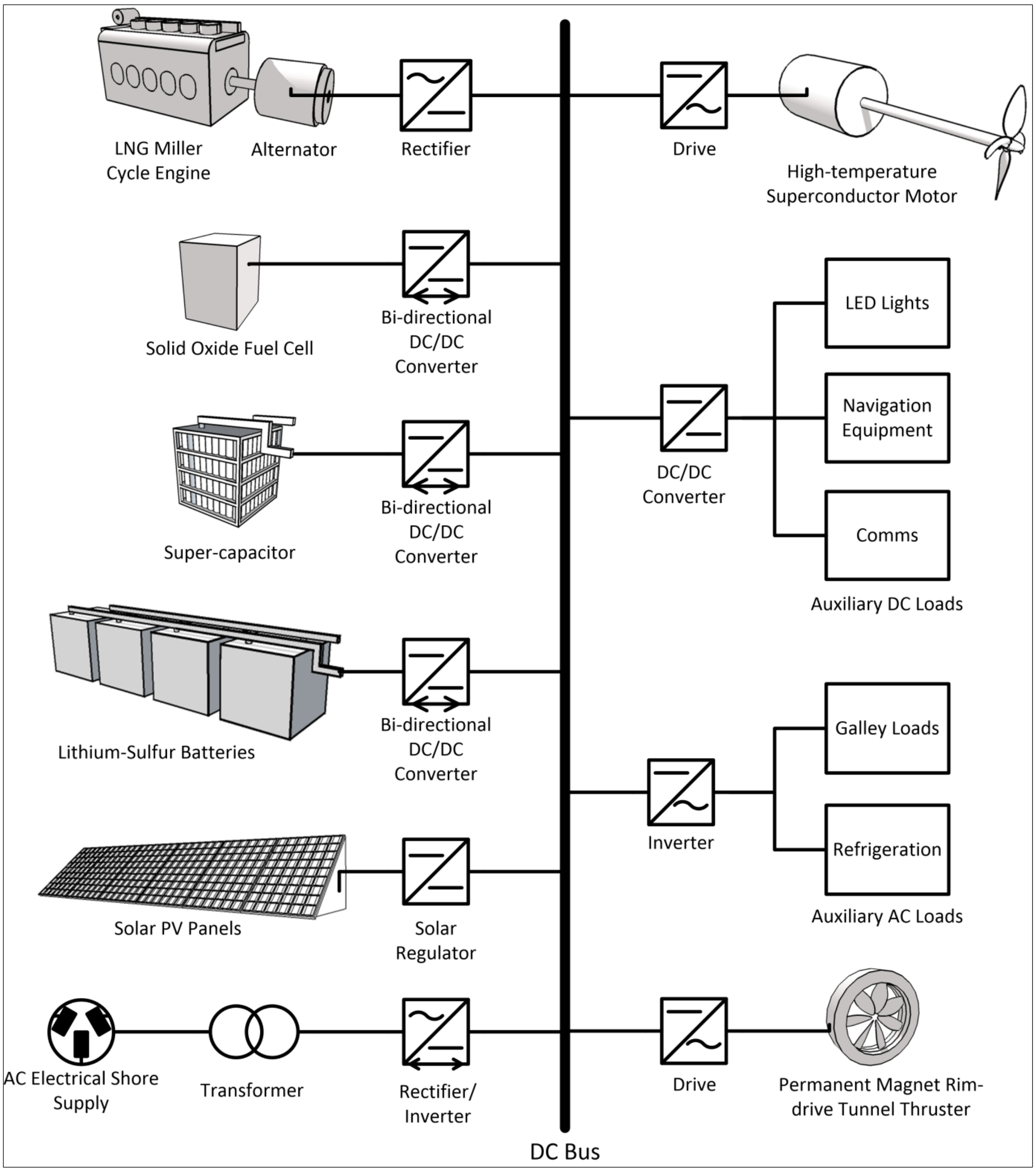

Figure 8. Possible future ship electrical system configuration, developed from Moreno & Pigazo[14] (2007, Figure 11) to show the latest trends.

High-power solid-state devices are an important enabling technology for high-power DC distribution in ships.[63] The rail industry has used high power DC distribution since the late 19th century in overhead and 'third rail' systems for powering electric trams and trains.[65] Common voltages used in rail DC systems are 750 V, 1.5 kV and 3 kV and solid state IGBT motor drives rated over 500 kW are commercially available.[66] Compact solid state inverters over 2 MW have been developed for the confined spaces in wind turbine nacelles.[67] The motor drive, converter and inverter components developed for modern trams, trains and wind turbines could be adapted to the marine environment to provide power conversion and control for high-power DC distribution in mid-sized vessels.

2.2.13 Summary of new concepts

Based on the assembled data, the innovative way forward includes:

- An increase in the use of solar PV;
- The commercialisation for marine vessels of lithium-sulfur battery, methane-fuelled SOFC fuel cell and HTS technologies;
- The use of high-power DC distribution in commercial vessels, with adaption of power conversion technology from electric vehicles, including DC rail traction systems.

These systems will need to be integrated with the developed fields of maritime electric propulsion.

2.2.14 Conclusions

Recent literature has been reviewed for potential contributions of electrical technologies to marine vessel efficiency. Electric vehicle and mains grid systems literature has been cited where details on marine applications of new technologies is scarce or non-existent.

Significant improvements in solar PV module price and efficiency have made the technology commercially feasible for augmentation of on-board electricity generation, but solar energy's contribution will be limited by solar irradiance and the vessel's catchment area. Within the next decade, electricity generation using high-temperature SOFC fuel cells is well-positioned to take advantage of a rapid increase in the use of LNG fuel for low emissions ship propulsion.

Lithium-ion battery technologies have been successfully commercialised for on-board rechargeable electrical energy storage. A likely performance breakthrough with lithium-sulfur technology will bridge the gap to metal-air and new flow battery technologies, which are unlikely to be commercially viable for vessel use within the decade. Augmentation of the power density of energy storage systems with supercapacitors is recommended for applications requiring frequent short bursts of high power and rapid recharging.

The use of permanent magnets is now widespread in marine electric propulsion motor offerings. Permanent magnets are enabling novel motor topologies, which are providing improvements in torque/speed performance, along with:

a) Improving the hydrodynamic efficiency of pod propulsors by providing a smaller cross-sectional area;
b) Enabling reduced length motors in submarines;
c) Elimination of hubs and shafts with rim-drive motors in tunnel thrusters.

High-temperature superconductor technology may be feasible in applications where high power density with reduced machinery size and mass is critical. The decreasing price of high-temperature superconducting wire has potential to facilitate commercialisation of HTS motors by 2020 due to improving costs relative to copper.

There is now a standard for high power DC distribution systems in ships. This form of electrical power distribution will facilitate the interfacing of increasingly diverse energy sources and loads, including:

a) DC energy sources, such as solar PV and fuel cells;
b) DC energy storage, such as batteries and supercapacitors;
c) High-frequency AC energy sources, such as high-speed alternators;
d) Low-frequency, direct-drive motors;
e) Traditional 50Hz/60Hz AC loads; and
f) DC loads, such as electronic systems and LED lighting.

Solid state power conversion devices are available with ratings suitable for implementing high-power DC distribution in mid-sized vessels.

It is likely that submarine, warship, icebreaker, cruise ship, ferry and recreational vessel applications will continue to lead the industry in the application of these technologies to electric propulsion. Tugs, coastal fishing vessels and coastal freighters also have potential for fuel savings by adopting these technologies.

2.3 Epilogue to "Emerging technologies in marine electric propulsion"

According to SAGE Journals article metrics, "Emerging technologies in marine electric propulsion"[10] was downloaded 893 times between 1 Dec 2016 and 31 Aug 2018. It appeared consistently in the monthly top 50 'most read' articles in the Journal of Engineering for the Maritime Environment (JoEME) during 2015 and 2016. In 2017, JoEME's 'most read' metric was changed from a monthly to a cumulative figure and in Aug 2018 the article was listed in the top three 'most read' JoEME articles in the previous 6 months. These metrics show that the article has achieved its purpose of increasing awareness among marine engineering designers and researchers of the opportunities for development and application of Marine Electric Propulsion (MEP) technologies.

The following sub-sections discuss feedback and technology developments that have occurred in the period between the publishing of "Emerging technologies in marine electric propulsion" in 2014 and the drafting of this thesis in 2018.

2.3.1 Solar PV developments since 2014

Figure 1 (page 8) plotted a unique combination of annual solar PV commercial and research efficiencies, along with the US weighted average PV system price to 2013. After 2013 the solar PV cost and efficiency trends have continued:

- The best research cell efficiencies increased from 44.7% in 2013, to 46% in December 2014, with a breakthrough by a collaboration between Soitec, CEA-Leti and Fraunhofer ISE labs. However there were no improvements in 2015 or 2016,[68] confirming the 2013 tendency to a tapering of research cell efficiency gains as technologies approach 50% efficiency.
- Average commercial cell efficiencies have continued along the linear trend line of approximately +0.35% per year shown in Figure 1.[69]
- The US prices of installed land-based PV systems have continued downwards since 2013 and in June 2017 were less than US$3.00 per Watt for residential, less than US$1.50 per Watt for non-residential and less than US$1.25 per Watt for utility-scale installations.[70] However, the downward price trend after 2014 slowed compared with the 2009 – 2013 period.[69]

SEIA annual reports after 2014 no longer included the metric "US weighted average PV system price". The reason for this is unknown, however it is not unexpected for several reasons. Utility-scale PV represented around 30% of US total PV capacity installed annually in 2010 and grew rapidly, to around 70% in 2016.[70] Since the costs per W for utility-scale systems are much lower than for small systems, the "US weighted average PV system price" metric was being increasingly skewed to the low side by utility-scale capacity roll-out. After 2013, the US weighted average PV system price is not a useful measure in the marine vessel context, as marine PV systems are, at this stage in their development, closer to residential scale than utility scale. The median PV system price for US residential installations, as reported by Lawrence Berkeley National Laboratory[69], will be a more relevant analogy for PV system prices in the marine vessel context.

Aside from further improvements in solar PV pricing, challenges remain with installing solar panels in limited topside space available on vessels and integration of DC solar energy into vessel electrical systems that are predominately still alternating-current. A key challenge in this regard is the energy density, specific energy and cost of energy storage systems, which have improved since 2014, but are still not yet able to match diesel fuel. The environmental advantages of providing an increasing percentage of a vessel's energy with solar PV instead of fossil fuels is well established. Overcoming these challenges is therefore important for the marine industry and the planet.

2.3.2 Fuel cell developments since 2014

The suggestion in section 2.2.5 (page 11) of the paper, of the imminent feasibility of applying Ceramic Fuel Cells Limited's SOFC fuel cell units to electricity generation on vessels, has been found impractical for two reasons:

1. The company Ceramic Fuel Cells Limited went into liquidation in March 2015.[71]
2. After reviewing "Emerging technologies in marine electric propulsion" Dr Howard Lovatt, Team Leader Electric Machines, CSIRO, advised the author on a Skype teleconference in April 2016 that the ceramics in commercialised SOFC fuel cells were fragile and intolerant of vibration and shock, hence unsuitable for use on a marine vessel.

The broader concept of using SOFC fuel cells on vessels with LNG fuel is not totally discounted. Research into SOFCs is continuing[72] and it has been found that the mechanical strength of SOFC ceramics can be improved using metal (eg. stainless steel) support structures in a technology known as Metal-Supported Solid Oxide Fuel Cells (MS-SOFC).[73]

The significant technical challenges in safely storing hydrogen fuel may be overcome in future by a CSIRO project starting in 2018 that is aiming to demonstrate the conversion of ammonia to high purity hydrogen for fuel cell vehicles using a metal catalytic membrane.[74] By storing and transporting hydrogen as ammonia, energy density is higher and costs lower[75] compared to gaseous or liquid hydrogen. Pure ammonia is hardly innocuous, however when compared to pure hydrogen, it has potential to improve fuel handling, logistics, safety and cost. The CSIRO project may therefore improve the viability of hydrogen fuel use in vessels. The implications for this on fuel cell development would mean that low-temperature fuel cell technologies such as PEM, that only use hydrogen fuel, would become viable in a shorter timeframe.

2.3.3 Rechargeable battery developments since 2014

In section 2.2.7 of the paper, it was suggested that the availability of lithium might limit the growth in the use of lithium-ion batteries. It has been claimed more recently that this may not be the only limiting factor in the use of lithium-ion batteries. It is estimated that each Tesla Model S battery pack, using $LiNiCoAlO_2$ (NCA) cells manufactured by Panasonic, contains approximately 15 kg of cobalt.[76] Corvus Energy uses $LiNiMnCoO_2$ (NMC) cells in its DNV.GL approved marine batteries, which also contain a significant quantity of cobalt. Examples of lithium-ion battery chemistries and their uses have been listed[76] and these are reproduced in Table 1. Note that the NMC battery chemistry used by Corvus Energy, is also used in Tesla Powerwall batteries.

Cathode Type	Chemistry	Example Metal Portions	Example Use
NCA	LiNiCoAlO2	80% Nickel, 15% Cobalt, 5% Aluminum	Tesla Model S
LCO	LiCoO2	100% Cobalt	Apple iPhone
LMO	LiMn2O4	100% Manganese	Nissan Leaf
NMC	LiNiMnCoO2	Nickel 33.3%, Manganese 33.3%, Cobalt 33.3%	Tesla Powerwall
LFP	LiFePO4	100% Iron	Starter batteries

Table 1. Commercialized cathode chemistries and metals required, excluding lithium.[76]

Analysts claim that the problem with cobalt is that the forecast supply is less than the forecast demand, which has led to a doubling of cobalt (LME) prices, from US$30,000 per tonne in Sept 2016, to US$60,000 per tonne in Sept 2017. However, Tesla and Corvus Energy are not the only companies ramping up battery production. A shortage of cobalt would improve the market for lithium-ion technologies that use less cobalt, or no cobalt at all, such as $LiFePO_4$, $LiMn_2O_4$ (LMO) used in the Nissan Leaf, and $LiFeMgPO_4$ used in Valence Technology's DNV.GL approved marine batteries. A shortage of cobalt would also improve the market for developmental battery technologies that don't require cobalt, such as lithium-sulfur.

2.3.4 Electric propulsion motor developments since 2014

Tesla and General Motors have so far used induction machine (IM) motors rather than permanent magnet (PM) motors in their electric vehicles (EVs).[77] This was thought to be primarily a cost consideration, as induction motors have the lowest capital cost due to mature manufacturing processes and lower-cost materials than PM motors. However, Bazzi and Krein[77] show that comparison of efficiency/load curves and even torque/speed efficiency maps can be misleading when selecting motor technology. Real-world motor efficiencies are sensitive to the vehicle duty cycle. They show that IM motors can achieve higher efficiency in EVs and hybrid electric vehicles (HEV) than PM or SRM motors, depending on the dynamic efficiency characteristics.

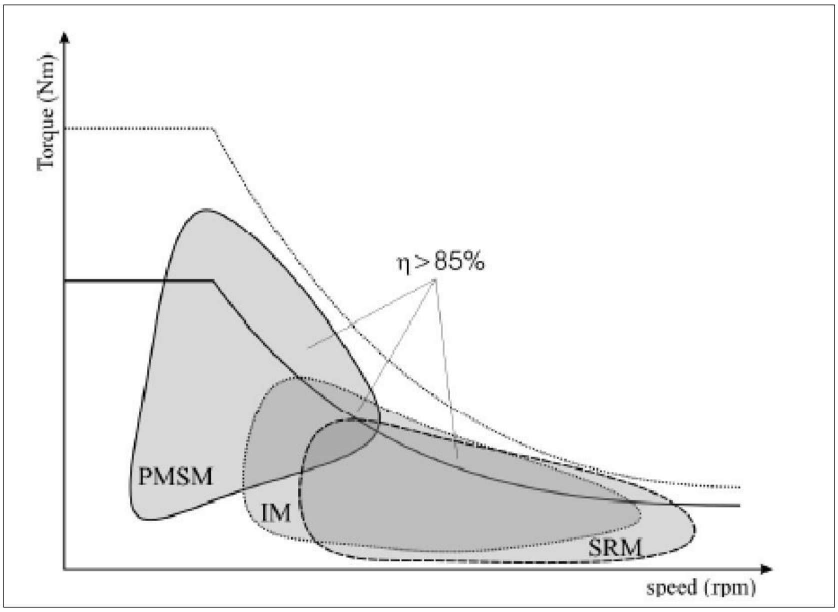

Figure 9. Overlay of induction machine (IM), PMSM, and SRM efficiency maps.[78]

Bazzi and Krein's figure 2,[77] is reproduced again in Figure 9. Although Bazzi and Krein caution that this figure can be misleading in the EV and HEV context due to its low sensitivity and relatively broad contours, it is useful in the marine electric propulsion context. It indicates that in the low-speed, high-torque region required for driving a propeller without a gearbox (<1500RPM), permanent magnet synchronous motors (PMSMs) have higher efficiency.

On the Skype teleconference in April 2016, Dr Howard Lovatt, Team Leader Electric Machines, CSIRO cautioned that permanent magnets have been found to be soluble in saltwater. This is an additional reason to ensure that electric motors in the marine environment, particularly in pod propulsors and rim-drive propellers, are well sealed. Saltwater will cause corrosion of iron and copper components, as well as shorting of wiring, in any electric motor. Effective seals are therefore essential for any type of electric motor used in bilge and sub-surface (eg. pod) marine applications.

2.3.5 Power electronics developments since 2014

Between 2014 and 2017, progress has been made in the development of commercial Silicon Carbide (SiC) power electronics devices:

1. In 2015 Mitsubishi Electric Corporation announced a 1500Vdc rail traction inverter with SiC electronics, claiming a 40% energy saving over silicon IGBT equipment.[79]
2. In 2017, ABB commenced offering its "Bordline" 10kW battery charger (3-phase 415 Vac to 110Vdc converter) for rail applications based on SiC technology, with a claimed significant reduction in size and >95% efficiency.[80] ABB doesn't yet offer SiC in its rail traction converters.

3. In 2017, the US Navy's Office of Naval Research (ONR) completed the development of a 10kV/240Amp (2.4MW) SiC module.[81]

These developments confirm the forecast in section 2.1.12, that Silicon Carbide technology has potential to play an increasing role in improving the efficiency of power conversion in mid-sized vessels.

2.4 Literature on modelling of Marine Electric Propulsion

The preliminary design of a vessel with a traditional diesel propulsion power train is a complex task.[82, 83] With an electric or hybrid propulsion system, the complexity increases significantly with each additional energy source and energy storage sub-system. Determining the ideal size of each sub-system requires modelling of multiple factors. A model to assist in preliminary design of electric and hybrid vessels will need to include modelling of:

1. Vessel hull efficiency
2. Propeller/waterjet efficiency
3. Sail performance (if applicable)
4. Wind and weather affects
5. Auxiliary power requirements
6. Multiple energy source options, such as:
    a. shore electrical energy,
    b. solar PV energy,
    c. sail regeneration energy,
    d. fuel generator/range extender.
7. Multiple energy storage options, such as:
    a. Battery,
    b. Supercapacitor
    c. Fuel tank.

Dupriez-Robin et al[84] proposed an approach for handling the complexity of a hybrid sailing vessel by modelling. Many have developed approaches for modelling the control systems for electric and hybrid propulsion.[85] However, there has been little progress on modelling of sub-system sizing in the preliminary design stage and the need to determine sub-system sizing prior to fine-tuning system performance.

2.5 Discussion

The following highly prospective technologies identified and summarised in the literature review were deemed (a) too resource-intensive, or (c) too time-consuming to investigate further during the limited project timeframe:

1. Batteries (including lithium-ion and lithium-sulfur)
2. Electric motors (including PM and high-temperature superconductor motors)
3. PEM and SOFC fuel cells
4. High power DC distribution
5. SiC power electronics.

The following subjects were chosen for further investigation in this project:

1. Modelling of marine electric propulsion to aid vessel preliminary design,
2. Application of Solar PV for marine electric propulsion.

Chapter 3: The significance of marine electric propulsion in Australia

Part of the research contained within this chapter has been published as W. Peter Symington & Jonathan R. Binns (2015), The dawning of the age of high-efficiency vessels, Australian Journal of Mechanical Engineering, 13:3, 154-162

3.1 Overview of Chapter 3

The market for lightweight, aluminium vessels of length 12 to 50 metres is dominated by Australian shipbuilders.[11] Based on industry discussions and ideas formed from the literature review, Marine Electric Propulsion development, was found worthwhile for particular focus in the Australian context.

It was identified in the early stages of this project that there is a window of opportunity for Australian shipbuilders to enter the electric vessel market. The market drivers were explored and a window of opportunity identified. It was determined that these should be highlighted to Australian industry, governments, and researchers by publishing the paper, "The dawning of the age of high-efficiency vessels" [12]. The paper forms section 3.2 of this chapter.

Section 3.3 of this chapter provides an epilogue to the published paper and highlights further developments between the publishing of the paper in 2015 and the drafting of this thesis in 2018.

3.2 The dawning of the age of high-efficiency vessels

3.2.1 Abstract

Transport depends on crude oil as a source of fuel for trucks, trains, ships and bitumen for roads. Europe has shown that, even with a strong commitment to emissions reduction, transport Green House Gas emissions will continue to rise relative to other sectors. As Australia's freight task increases and as fuel supply risks increase, the need for change is also increasing. Investment will be required in transport fleet expansion and replacement, meaning that now is an opportune time to review our transport paradigm.

Sea transport is no different to road, rail and air in its ability to leverage improvements in engine efficiency, materials, logistics management, control systems, renewable fuels, hybrid, solar and energy storage technologies. However sea transport has two unique advantages over other transport modes:- a low cost of infrastructure and the capability of harnessing wind by direct conversion of kinetic energy.

The development of high-efficiency vessels and market drivers are close to a tipping point for rapid evolution. A possible step in this evolution is the development and application of high-efficiency vessel technologies to improve the sustainability of remote communities and the tourism industry. This would have strong synergies with the Australian high-speed shipbuilding industry's world market leadership.

3.2.2 Introduction

By 1895 the Cutty Sark sailing clipper was sold because it could no longer compete with fossil-fuelled steam ships on the wool trade route between Australia and England.

On 4 October 1907 Theodore Roosevelt said,[86] "The conservation of natural resources is the fundamental problem. Unless we solve that problem it will avail us little to solve all others." One hundred and six years later, the fundamental problem is far from solved.

In 2008 one author was driving many kilometres in regional Queensland, sharing the Bruce Highway with diesel-fuelled semi-trailers carrying the sustenance of the state. During this time, fuel prices were soaring, causing hardship to truck operators and remote communities. The documentary, "*An Inconvenient Truth*" had raised awareness of greenhouse gas emissions and climate change. These events inspired a top-down review of alternatives for freight transport and the results are summarised in this paper.

Due to the combined influences of Australia's geography and customers' requirements, no single mode of transport can meet all of Australia's future domestic long-haul freight transport requirements. A corollary of this is that no mode of transport should be excluded from consideration. All feasible options for improving fuel efficiency and reducing greenhouse gas (GHG) emissions - of every mode - will need to be encouraged by policy makers, designed by engineers and implemented by industry. This paper presents a development pathway for sea transport. Improvement in other transport modes and intermodal transportation have been considered by others, for example, Brinsmead[87], Kaspura[88] and Kilsby[89].

3.2.3 Crude oil dependence

Transport in Australia relies heavily on crude oil and its derivatives for fuel. As a relatively isolated and sparsely populated nation, the transport sector and oil have disproportionate significance to Australian domestic and international trade.

As well as providing the bulk of fuel that propels freight transport, crude oil is the primary source for bitumen used to build and repair Australia's extensive road network. Increases in the costs of bitumen, diesel, aggregate and other inputs have increased the burden of road works on government finances. For example, the cost of building and maintaining roads increased well over the ABS Consumer Price Increase (CPI) for the 10 years to June 2012.[90]
In addition to road maintenance cost increases,

> *strong growth in the use of higher mass limit freight vehicles, together with an increase in passenger use, is placing pressure on the condition of the existing road network, requiring significant investment in road asset preservation, renewal and maintenance.*[91]

Long distances and relatively low volumes of freight mean that prices of goods in remote communities are strongly coupled to fuel prices. The potential consequences of Australia's dependence on oil were shown by the 2008 oil price spike's effects on remote communities. The effects were reported in the ABC 7.30 Report segment, "*High petrol prices devastate Torres Strait communities*".[92] The 2008 oil price spike was a recent warning sign for the nation of future price volatility.

Improvements in oil extraction technology are leading to an increase in oil production in North America. The International Energy Agency (IEA) advised[93] that these increases in production have barely managed to keep up with supply disruptions from Middle Eastern and North African oil producers. These issues of geopolitical turmoil continued to impact on oil supply and demand in 2012/13 and are projected by the IEA to continue to have a significant impact on oil supply through to 2018.[94]

Oil production in Australia is projected to peak around 2013, meaning an increasing reliance after 2013 on imported oil, as shown in Figure 10.

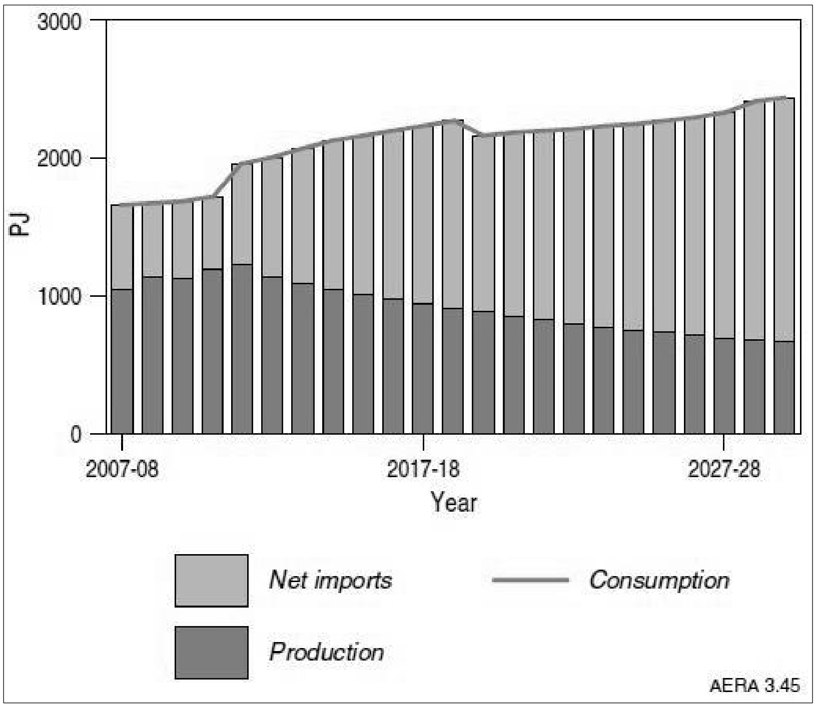

Figure 10. Australia's forecast oil supply-demand balance.[95] Total production of oil is predicted to peak in 2013 and from then on decrease. Total consumption is predicted to continually increase through to 2030, necessitating increases in oil imports.

A greater reliance on imported oil is going to increase Australia's susceptibility to global supply-side risks and their implications.[88] The increasing volatility of our fuel supply and above-CPI increases in the cost of building and maintaining roads are significant and growing risks to a business-as-usual approach to freight transport. It is likely that by 2020 the forecast serious problems caused by Australia's crude oil dependence[88] will be realised. As a result, there will be increasingly compelling opportunities for high-efficiency transport and alternative fuels. This is regardless of emissions considerations.

3.2.4 The European experience

Shell[96] identified the relationship between fossil fuel dependency and GHG emissions:

> *Even if it were possible for fossil fuels to maintain their current share of the energy mix and respond to increased demand, CO_2 emissions would then be on a pathway that could severely threaten human well-being. Even with the moderation of fossil fuel use and effective CO_2 management, the path forward is still highly challenging.*

Remaining within desirable levels of CO_2 concentration in the atmosphere will become increasingly difficult.

European countries have been pro-active in reducing carbon dioxide emissions. For example, the European Union (EU) has had an Emissions Trading Scheme (ETS) in place since 2005. Figure 11 shows that, despite significant efforts to reduce emissions and significant reductions in all other sectors, transport sector emissions in Europe have continued to rise. This shows that transport is the most difficult sector in which to achieve significant emissions reduction.

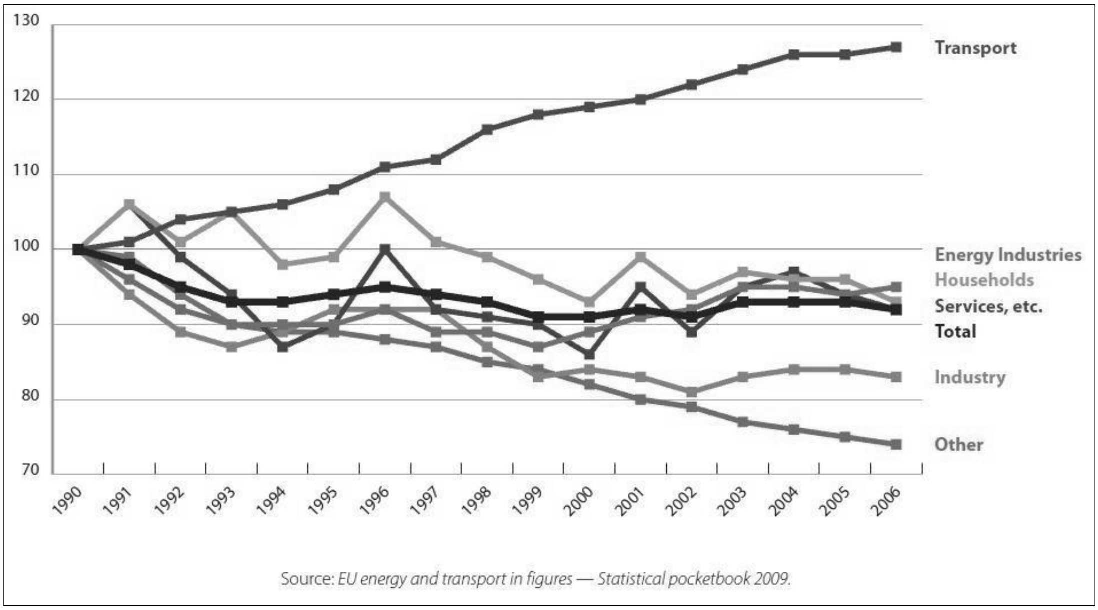

Figure 11. Change in greenhouse gas emissions in Europe (EU-27), by sector, since 1990 (1990 = 100).[97]

Solving the problem of growing transport sector emissions is now a high priority for the European Commission (EC), as evidenced in a report by the European Environment Agency,[98]

In the EU context, Commission President Barroso's political guidelines for the new Commission made it clear that maintaining momentum towards a low-carbon, resource-efficient economy, particularly towards de-carbonising the transport sector, would be one of the priorities of his second term…. Climate mitigation - including in the transport sector - has thus moved to the heart of transport policy, and indeed to the heart of EU policy.

Furthermore, the report urged policy-makers to immediately adopt a broad range of transport sector emissions reduction strategies.[98]

The Australian Government has plans for alternative action on emissions reduction. The government's initial focus will be on sectors other than transport. This seems sensible, as there are plenty of 'low hanging fruit' in other sectors that, as demonstrated in Europe, can quickly achieve significant emissions reductions. However the European experience also demonstrates that transport sector emissions cannot be ignored. This is crucial to understand in the Australian context, considering the Australian transport sector's disproportionate significance to domestic and international trade.

The Europeans have found that all transport modes need to be considered as part of an emissions reduction strategy. Importantly, the European Commission is planning to increase use of sea freight transport:

> *Thanks to Europe's long coastline and large number of ports, the maritime sector is a valuable alternative to land transport. The full implementation of the European maritime space without barriers and the maritime transport strategy for 2018 can make the 'motorways of the sea' a reality and exploit the potential of intra-European short sea shipping.*[97]

In 2012 the transport sector contributed 91.5 Mt CO_2-e, or 17%, of Australia's national inventory emissions. Transport sector emissions increased by 47.5% between 1990 and 2012.[99] The Australian transport sector's share of emissions will follow the European trend over the next decade, because rapid change in this timeframe is unlikely.[88] As transport emissions rise and other sectors' emissions fall, transport's share of total emissions will increase and this will lead to growing pressure for improvement. Any sustained national focus - by any means - on lowering GHG emissions in Australia will strengthen the case for changes to the nation's transport paradigm.

3.2.5 Upgrading the fleet

In Australia, the national freight task will almost double between 2000 and 2020.[100] This growth is compounding oil dependence and emissions issues.

To cater for the growing freight task, the size of Australia's transport fleet, including trucks, trains, planes and ships, will have to grow. Concurrently, vehicle replacements will be required for reliability, fuel efficiency and emissions reduction.

Dramatic events culminating in the US Government's bailout of the US automobile manufacturing industry in 2009, demonstrated the danger of an industry ignoring fuel efficiency improvements and emissions reduction for a decade.[101, 102] By contrast, the survival of the Global Financial Crisis by automobile manufacturers in Japan, Korea and Germany demonstrated the resilience provided by a history of continual fuel efficiency improvement. The story will be similar in the truck manufacturing industry. As low-emissions technology leaders, European truck manufacturers (Scania, DAF, Mercedes-Benz, Volvo, and Iveco) are likely to maintain their dominance of the long-haul truck manufacturing industry. Keeping up with the freight task, improving fuel efficiency and reducing transport emissions will require significant investment in new vehicles. As highlighted by Volvo Australia,[103] European truck manufacturers are well placed to benefit from this investment.

Australia has the opportunity and capability to develop the European 'motorways of the sea' concept and divert an increasing share of the domestic freight transport task and fleet replacement capital into high-efficiency shipping. As shown by the European car and truck manufacturers, significant national benefits would be derived from this.

3.2.6 The forgotten mode

Sea transport options have been notably absent from the Australian domestic transport focus.[100, 104] This is despite:

1) Australia's shipbuilding industry is the world leader in fast and efficient aluminium vessel design and construction.[11]

2) More than 80% of the Australian population lives within 50km of the coast.[105]

3) Many of Australia's remote communities are only accessible by sea and air.

Sea transport technology, in its most widely used current incarnation of steel 'super' ships, provides very significant efficiencies of scale and is therefore relatively fuel efficient. However, where they are powered by bunker oil, super ships are not a shining example of good emissions practice. Tim Flannery described the emissions from international shipping:[106]

> *One of the foulest pollutants on Earth is the fuel oil that powers shipping. Over the past few years the volume of international shipping has grown by 50 per cent, meaning that cargo ships have become a leading source of air pollution. The matter that powers these vessels is the left-overs from the production of other fuels, and so thick and full of contaminants is it that it must be heated before it will even flow through a ship's pipes. Satellite surveillance reveals that many of the world's shipping lanes are blanketed in semi-permanent clouds that result from the particulate emissions from ships' smokestacks.*

Significant improvements in shipping fuel efficiency and emissions reduction are possible.

3.2.7 Sailing with a renewed energy

Tim Flannery also suggested,

> *Yet solving this problem is potentially easy; after all, until little more than a century ago maritime transport was wind-powered. Using modern wind and solar*

technologies and energy-efficient engines, sea cargo may, by the middle of this century, once again be travelling carbon-free.[106]

Figure 12. The Cutty Sark, low-GHG emissions freighter.

Indeed, the Cutty Sark (Figure 12) was a cargo ship that provided a fast freight service for its time, with very high fuel efficiency and low GHG emissions. It was one of the last of its type and was superseded by fuel-dependent and emissions-intensive vessels.

Sailing vessel technology did not disappear and has been steadily improved over the last century in recreational and racing sailing vessels. Excellent examples of current technology adapted to commercial vessels are the sailing catamarans designed by Incat Crowther (Figure 13) and Graham Parker in Australia. These sailing catamarans are 25 to 32 m in length and provide tourist trips to the Great Barrier Reef from Cairns and Port Douglas. They are especially significant as they operate successfully in competition with diesel-powered vessels. Unlike the Cutty Sark, these sailing catamarans are hybrid vessels, with diesel engines for travelling in adverse winds or calm conditions.

Figure 13. Commercial sailing catamaran Wavedancer designed by Incat Crowther (1986). Photo courtesy of Quicksilver Cruises, http://quicksilver-cruises.com.

German company SkySails has recently adapted large cargo vessels with 'sky sails', which operate in a similar manner to kiteboarding kites, but on a much larger scale. The sky sails have areas between $120m^2$ and $600m^2$ and are positioned up to 600m above the vessel, providing significant fuel efficiency improvements, exceeding 10%.[107]

The B9 Energy Group in Northern Ireland has a concept design for a 100m sail and biofuel powered cargo ship that will operate without fossil fuels. A model of the ship was tested at the University of Southampton in 2012.[108, 109]

There is a mistaken view that sailing ships are a symbol of a past era. The rapid adoption of wind turbines for fixed electricity generation shows that wind is a viable renewable resource. Mankind has used sails to directly convert wind kinetic energy to vessel kinetic energy for thousands of years. No other conversion mechanism has proved more effective for harnessing wind for transport propulsion. While renewable energy cannot yet provide 100% of the propulsion requirements of a super ship or a high-speed ship, fuel savings of 10% and more are significant and encouraging. Modern sailing vessels like that in Figure 13 could indeed be a symbol of the future of sea transport.

3.2.8 Solar energy drivers

Solar photovoltaic (PV) panels have been used to provide auxiliary power in sailing vessels for several decades. Ongoing improvements in solar PV efficiency and reducing costs[110] mean that solar power is an increasingly viable energy source for vessels. The potential for solar energy to contribute to vessel propulsion was highlighted by the first global circumnavigation of a solar-powered vessel, the MS Turanor PlanetSolar, in May 2012.[1]

Efficient marine electric drives and high-energy-density batteries are important enablers for wider adoption of solar energy to vessel propulsion. Interesting recent developments in electric propelled recreational vessels include the Oshunpro prototype tested in the Noosa river in 2011 [111] and the Solar Pacific Cruiser prototype built in Hervey Bay.[112, 113]

Marine electric drives have been used since the early 20th century in diesel-electric propulsion for submarines, warships, cruise ships and ice-breakers.[15] In recent decades, electric motor and battery development has advanced rapidly in hybrid and electric land vehicles. In parallel with this, the use of electric driven marine propulsion is increasing for various reasons (Symington et al [10]), such as facilitation of:-

- more flexible machinery arrangements;
- low noise operation;
- more economical running with partial loads or large auxiliary loads;
- increased manoeuvrability, for example via Cyclic and Collective Pitch Propulsion (CCPP) or pod propulsors;
- increased redundancy;
- solar energy in hybrid systems.

Recent notable applications of electric driven propulsion include the MS Turanor PlanetSolar vessel, the Oasis class cruise ships, the Solar Sailor ferries, Unmanned Ocean Vehicles (UOVs) and Autonomous Underwater Vehicles (AUVs).[1, 16, 114, 115]

3.2.9 Super ship concepts

The International Maritime Organization (IMO) is taking action to reduce shipping emissions. The 59th session of the IMO Marine Environment Protection Committee (MEPC) agreed in 2009 to disseminate a package of interim and voluntary measures to reduce emissions.[116] The 62nd session of the MEPC introduced mandatory measures, including the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships.[117] Cosgrove, Gargett, Evans, et al.[118] estimate the emissions reductions of the application of these and other measures on Australia's domestic fleet.

Two major steel shipbuilders have recently developed excellent concept designs for 'super' ships propelled by a hybrid system of wind, gas fuel and solar energies. STX Europe's EOSEAS concept comprises a 5-mast, 305m multi-hull cruise ship utilising LPG, wind and solar power.[119] In 2009, NYK of Japan published the Super Eco Ship 2030 concept design utilising a traditional monohull, gas fuel cells, wind and solar power. NYK indicate that the Super Eco Ship 2030 may be able to be built by 2030.[120] However, the premise that rapid efficiency improvements will be easily achieved by adapting new technology to existing super ships may be optimistic because:

1. The complex structural design of super ships is not readily adapted to the very different stresses of wind propulsion.
2. The timeframe for building a super ship is approximately 3 years, so the design-build-operate-feedback-design cycle for super ships does not facilitate rapid evolutionary change.
3. It assumes that international shipping operators will pay for significant changes to super ship design. This ignores flags of convenience, which have been consistently and effectively used since the mid-20th century to avoid regulations that might threaten lowest cost. Until the IMO can demonstrate that its new measures are internationally enforceable, this will remain an impediment.
4. The pace of implementing super ship efficiency improvements was hampered by an increase in spare shipping capacity and a shipbuilding downturn due to the Global Financial Crisis and the subsequent protracted recovery.[121, 122]

Progress in low-fuel and low-emissions propulsion is likely to proceed more rapidly via an evolutionary path, commencing with smaller vessels operating within enforceable national boundaries, for which the transition steps are smaller and faster. The development of fossil-fuelled vessels between 1788 and 1950 and high-speed aluminium vessels between 1983 and 2010,[11] show that increases in scale will evolve with increasing confidence in technology, design and performance.

This supposition has important implications for Australia. It suggests that an established high-efficiency vessel design and build capability might be more significant in a nation gaining market share of the world’s future shipbuilding industry than a pre-existing steel super ship manufacturing industry. If so, this is one more factor in a convergence of factors that place Australia in a unique position.

3.2.10 A manufacturing industry in which Australia is the world leader

Australia is the world leader in high-speed aluminium shipbuilding. Australian aluminium shipbuilders built more than 70% of the world’s contracted high-speed vessels in 2008.[11] In second place was Italy with less than 10% and third was China. Australian companies contributing to this remarkable achievement are located in the states of Tasmania, Western Australia and Queensland:

- Incat in Tasmania

* Richardson Devine Marine in Tasmania
* Austal in Western Australia
* Strategic Marine in Western Australia
* SBF Shipbuilders in Western Australia
* Aluminium Marine in Queensland

The technology leadership underpinning this market leadership was clearly demonstrated by Austal winning a US Navy contract to build a high-speed Littoral Combat Ship (LCS) valued at US$432.1 million, with options for nine additional LCS ships over five years. This is in addition to US Department of Defence contracts to build Joint High Speed Vessels (JHSV) as part of a 10-vessel program valued at up to AUD$2 billion.[123]

Some key features of high-speed vessels, namely sleek, lightweight multi-hulls, are also applicable to high-efficiency vessels. The Australian shipbuilding industry is therefore well-positioned to supply an emerging world market in high-efficiency vessels.

3.2.11 Another industry where Australia is a leader

There are in fact two transport manufacturing industries in which Australia is a world leader. The second is in fuel, solar and wind hybrid propulsion vessels. Solar Sailor Holdings Ltd was established in the late 1990s to commercialise a patented solar wing. With government assistance it built the Solar Sailor ferry (Figure 14) for the Sydney 2000 Olympics.

As a demonstration of the growing market for these vessels, Solar Sailor Holdings Ltd has recently built new hybrid propulsion vessels for companies in Hong Kong and mainland China.

Figure 14. Solar Sailor Ferry. Photo courtesy of Ocius Technology Ltd, http://ocius.com.au.

In March 2011, Solar Sailor Holdings Ltd conducted sea trials of the Solar Albatross (Figure 15), which was built for the Hong Kong Jockey Club.[114]

Figure 15. Solar Albatross trials in Hong Kong. Photo courtesy of Ocius Technology Ltd, http://ocius.com.au.

Australia's world leadership in two strategic marine transport industries adds two more factors to the list. However, the list is lacking in some key factors, including a strategy and supportive marine industry policy framework for fully applying these capabilities to national benefit and ultimately, global benefit.

3.2.12 A path beyond business as usual

There is no single, 'silver-bullet' solution to the fundamental problem. For example, the economists' solution of a global price on emissions is unlikely to be achieved. According to Shell,[124] "*A positive outcome requires a series of proactive, far-sighted, and co-ordinated national and international policy developments that, to date, seem beyond the bounds of plausibility*." However, incremental improvements by individuals, corporations and governments, in aggregate, have potential to significantly improve fuel efficiency and reduce emissions.

Kevin[125] points out that Australia's challenge with climate change is no longer a question of climate science, but of formulating engineering solutions. He makes the statement,

> *Engineers could and should be at the forefront in designing and proposing safe and sustainable energy solutions. We should certainly not be lagging in the rear, defending the continued use of what we now know to be high-risk and obsolete carbon-burning systems.*

He further advises that for an effective response, engineers at all levels need to step forward, develop and drive necessary changes. How might engineers, the marine industry and policy-makers in Australia work towards solving part of the fundamental problem?

A path for harnessing Australia's world-leading marine design and manufacturing capabilities in reducing transport sector oil dependence and emissions could involve replacing fossil-fuelled engines, by a systematic process of vessel retrofits and new-builds. With development of technologies and increasing scale, this process could mimic the growth and dominance of the Australian fast ferry industry. If we classify this process into steps, by matching vessel scale with applications, it could look something like this:

1. Leading-edge high-efficiency vessel technologies and shipbuilding capability mobilised to reduce vessel fossil fuel consumption and improve the sustainability of remote communities and the tourism industry.
2. Apply this emerging capability to mid-sized vessels to reduce the oil dependence and improve the sustainability of Pacific island nations.
3. As technologies and scale evolve, apply honed capabilities to inter-regional and inter-state freight transport, particularly in niches where efficient sea transport is the most cost-effective mode.
4. As vessel sizes grow to international freight capability, increase manufacturing automation and significantly expand manufacturing capability to cater for the growing world market.

With well-coordinated action by industry, researchers and policy makers, the rate of evolution for high-efficiency vessels could be at least as rapid as it was for aluminium high-speed vessels. Australia is well-positioned to lead the world in this endeavour.

3.2.13 Where high-efficiency vessels might develop and why

Efficient sea transport technologies are successfully competing with fossil-fuelled vessels on Far North Queensland reef trips and Hong Kong harbour ferry trips, but they are not yet sufficiently developed to match efficient road or rail transport on inter-state routes - other than to Tasmania (across Bass Strait). If the technologies are to evolve rapidly at small scale, it will be on routes to islands, where sea transport is the only viable option for heavy freight. Australia has a long coastline, along which island communities are located at relatively large distances.

The use of wind energy is enhanced by the Great Barrier Reef off the coast of Queensland, which provides protected coastal waters, with little reduction in wind energy. The Queensland coast is therefore an ideal waterway for developing and operating high-efficiency vessels.

Figure 16. Zone of peak, year-round solar energy.

The map in Figure 16 shows regions of the world lying within +/- 30^0 latitude of the Equator. This is where solar energy is most useful over the full year. As NYK has mentioned, this will be a critical factor in the adaptation of solar energy for use on vessels.[120] Northern Australia is clearly within the zone, as are countries in Central America, South America, Africa, Southern Asia and South-East Asia.

The commercial sailing catamarans operating out of Cairns and Port Douglas and the Solar Sailor ferries are showing the world the way forward for high-efficiency transport. Further development and implementation in Australia of these technologies will have benefits in terms of sustainability of our tourism industry, training of crew and establishment of support industries for operating future vessels.

Increased recognition of the potential opportunities by Australian governments is needed. Development of an active and supportive policy framework can ensure that national benefit will be derived from the window of opportunity presenting itself to Australian shipbuilding and sea transport industries. With coordinated action, Australia will be well-placed to lead the way in the emerging high-efficiency vessel market.

3.2.14 Conclusions

The age of high-efficiency vessels is dawning. There is a concurrence of factors that place Australia in an important position globally with regard to the development and use of high-efficiency vessels:

1. As a relatively isolated and sparsely populated nation, the transport sector has disproportionate significance to Australian domestic and international trade.

2. More than 80% of the Australian population live within 50km of the coast.
3. Australia has many remote communities and neighbouring island nations that are only accessible by sea and air and are vulnerable to oil supply volatility.
4. Wind is a key renewable resource. Direct conversion of wind kinetic energy to vessel kinetic energy is a well-proven method of harnessing wind for transport. Australia is a leader in the commercial use of modern sailing technology.
5. Australia is the world leader in high-speed aluminium shipbuilding.
6. Australia is a world leader in hybrid fuel, wind and solar propulsion vessels.

Recognition of these factors and coordinated action by Australian policy-makers, researchers and industry will be required to reify a solution of global significance.

3.2.15 Disclosure statement

Symington[126] holds a patent for a hybrid vessel concept. The authors declare that there is no conflict of interest.

3.2 Epilogue to "The dawning of the age of high-efficiency vessels"

There have been improvements in the market drivers for electric propulsion since the article was published in November 2015. The Norwegian government advised in May 2018 that it will ban all polluting ships from its UNESCO World Heritage fjords by 2026. This decision will require all cruise ships and ferries operating in the fjords to move to zero emissions technologies. Electric vessels are the only feasible technology currently available that will meet the new requirements. DNV-GL, which first created class rules for electric ferries in 2012, now has 94 vessels with batteries in its classification register and in mid-2018 is registering almost one electric vessel per week.[127]

While Norway is leading, it is not on its own. In an April 2018 meeting of the IMO Marine Environment Protection Committee, 173 countries (including Australia) agreed to lower CO_2 emissions in shipping by 50% by 2050 compared to the 2008 levels. Only Russia, Saudi Arabia and the USA opposed the proposal.[128]

Following publication, the article was highlighted to Australian politicians and shipbuilding industry leaders. According to Taylor & Francis Online article metrics at 31 August 2017, "The dawning of the age of high-efficiency vessels" had been viewed 122 times since it was published. However, as at August 2018 there has not been significant action by Australian state or federal governments on the recommendations.

Feedback on the paper from Australian shipbuilders has been positive and as at August 2018 some development of mid-sized marine electric propulsion concepts has commenced.

Between 2015 and 2017, there was continuing development of high-efficiency vessels in Australia. Recent examples are:

- "Ellie J" solar/electric ferry built in Queensland by Scruffie Marine in 2016 and currently operated on the Swan River in Perth by the Little Ferry Company. This vessel follows the European examples of "Ar Vag Tredan" and "Ampere" in demonstrating the technical and commercial viability of marine electric propulsion for short-run ferry routes, as explored in Section 4.2.
- "Kato", a 20m solar/electric, carbon-fibre sailing catamaran built by Noosa Marine and operating out of the Gold Coast.[7] This $2.8M cruising vessel is capable of electric motoring speeds of 10 knots. It is also capable of sailing speeds in excess of 25 knots, while regenerating up to 10 kW of power.

Both "Ellie J" and "Kato" are therefore important vessels in the development of marine electric propulsion in Australia. The electric propulsion systems and batteries in both vessels were sized and supplied by Mr Claude Desjardins. The solar PV power systems in both vessels were sized and supplied by Mr Phil Chapallaz of Solar4RVs.

Chapter 4: Electric vessel modelling

Part of the research contained within this chapter (Section 4.2) has been published as W. Peter Symington & Claude Desjardins (2017), The Little Ferry Setting a Big Example in Urban River Transport, Institute of Electrical and Electronics Engineers (IEEE) Transportation Electrification Community (TEC) Newsletter, June 2017 Issue.

4.1 Preliminary Design Modelling Methodology

Chapter 2 introduced two key areas of focus for this project:

1. Development of a model for Marine Electric Propulsion to assist in vessel preliminary design. The project work on this topic is described in Chapter 4.
2. Development of a solar PV system design methodology for marine vessels. The project work on this topic is described in Chapter 5.

The early stage of the project involved investigation of a computer-based model of electric vessel sub-systems and suggested the power model structure shown in Figure 17.

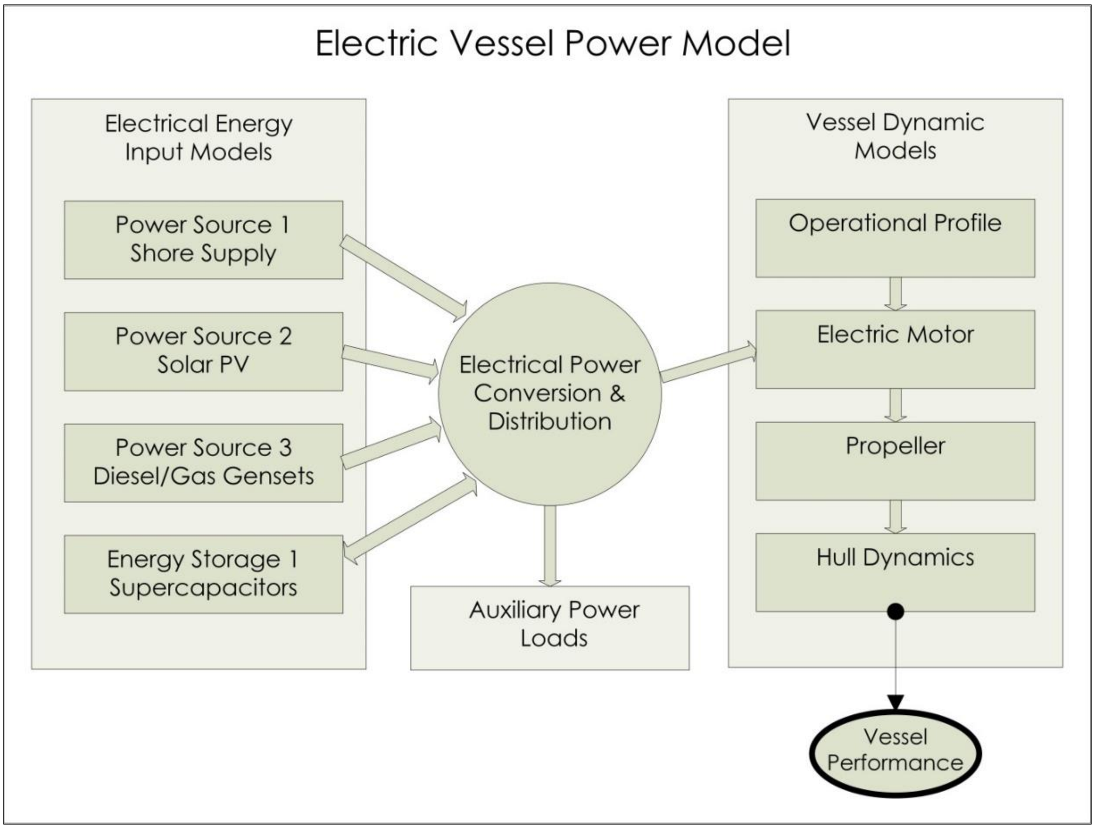

Figure 17. Plan for Modelling Electric Vessel Subsystems

4.1.1 Moody's preliminary power prediction model

In his thesis, "Preliminary power prediction during early design stages of a ship",[13] Moody compared a range of vessel powering models for displacement monohulls, aiming for a broadly applicable and easily programmed model requiring minimal input data. He compared Fung and Holtrop's (MARIN) smooth water hull resistance methods and settled on Holtrop's (MARIN) method (Moody[13] section 3.2.13 and Figure 18). Moody also compared methods for wind, sea state and propeller resistance calculation.

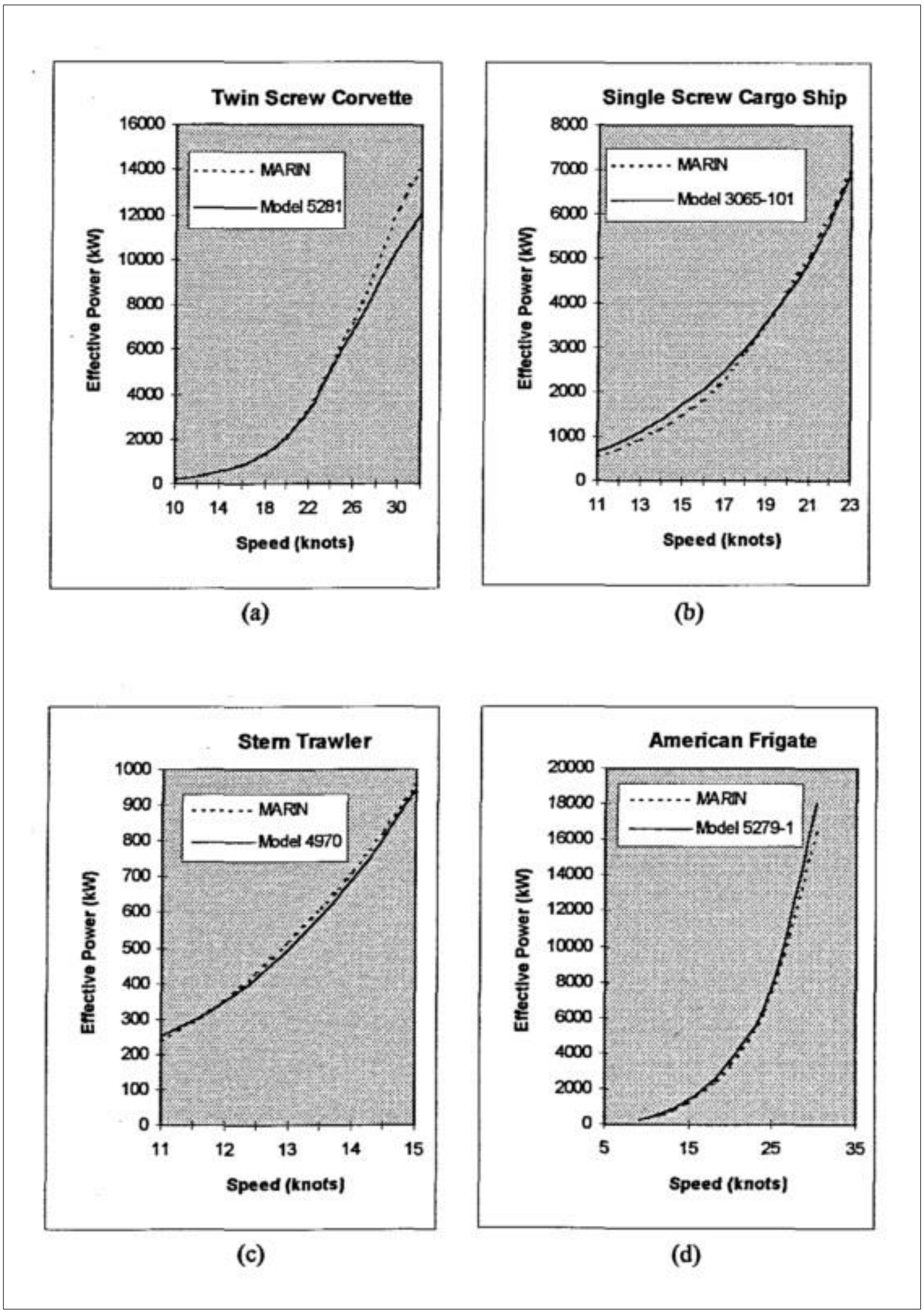

Figure 18. Moody's comparison of speed-power curves using MARIN method.[13]

Moody found that for quick analysis with the limited data available during a vessel preliminary design, the most suitable methods were: [13]

- Holtrop's (MARIN) model for hull resistance prediction and calculating propeller coefficients.
- Use of the Wageningen B-screw Propeller Series for estimating propeller open-water efficiency and rate of rotation, due to its range of two to seven blades, rather than the Gawn Series which only applies to three-bladed propellers. This choice should be reviewed for Marine Electric Propulsion, as Moody also found that the Gawn Series handled a larger P/B range and pitch diameter range than B-series and in the author's experience, most propellers currently available for electric propulsion have three blades.
- Estimating wind speed from significant wave height using the 11th ITTC proposal.
- Calculating wind resistance using the simple empirical equation developed by Taylor.
- Calculating added resistance due to sea state (waves) using the method of superposition.
- Moody compared the Holtrop and Mennen's method with Fung's method for calculating appendage resistance and chose the former due to Fung's method only being applicable to twin screw ships.
- A modification of Newton's formula for hull fouling resistance, so that it incorporated findings from RN and USN to resolve an increase in skin friction of 28% at six months out of dock (see Figure 19).
- Use of the 1984 ITTC formula for calculating hull roughness.

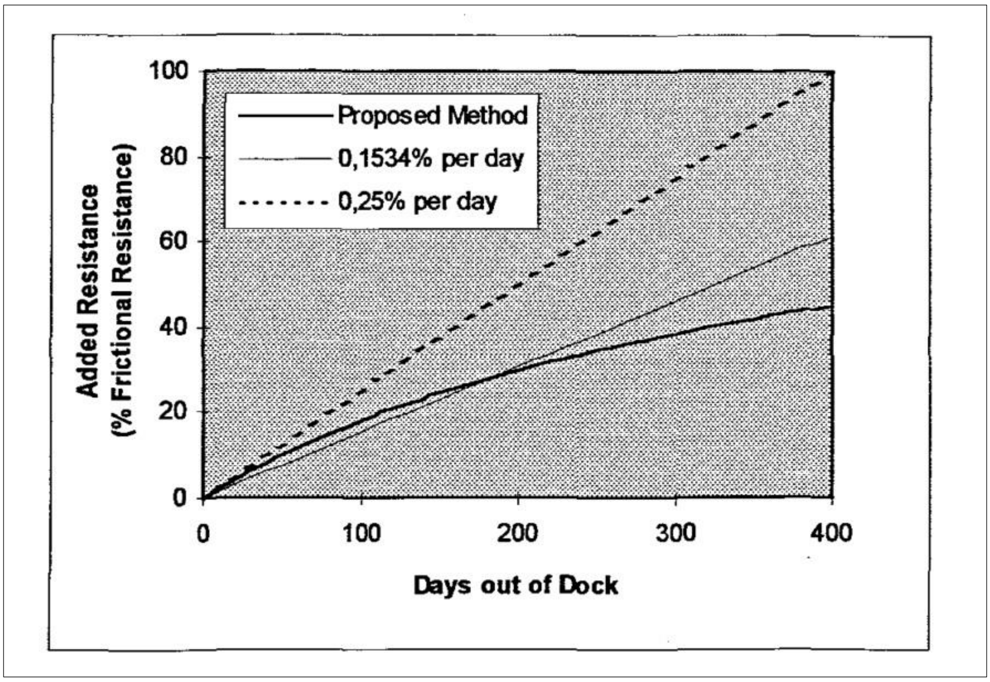

Figure 19. Moody's hull fouling resistance method compared to RN method.[13]

Moody included his Pascal code in his thesis appendices. Adapting Moody's code to current modelling software would enable electric propulsion modelling to build on Moody’s work with regard to vessel preliminary hull and propeller design. This would be conducive to modelling Marine Electric Propulsion, as the relative efficiency of the code would also enable rapid calculation of vessel sea state responses when estimating route performance and range.

4.1.2 Adaption of Moody’s model to Matlab

Moody's 1996 Pascal code was re-generated using Optical Character Recognition (OCR). The resulting text file was then parsed using Free Pascal Compiler (FPC). This included amendment of compiling errors related to OCR errors (1/l, 5/S, :/i, etc.) as well as modification/conversion of calls to old subroutine libraries no longer recognised by the FPC.

Several redundant variables in the original Pascal code had to be removed to prevent errors in the present-day FPC compiler. After reviewing formulas in the code, a runtime error in the original Pascal calculation of Model Correlation Coefficient was amended.

Once an executable file was generated from the original Pascal code, a Matlab Graphical User Interface (GUI) was developed (see Figure 20). The Matlab GUI (Power_exeGUI) enabled rapid iterative testing of the hull and propeller model parameter ranges. It was then possible to test the Pascal executable to ensure that its inbuilt formulas produced results in accordance with Moody's original thesis results.

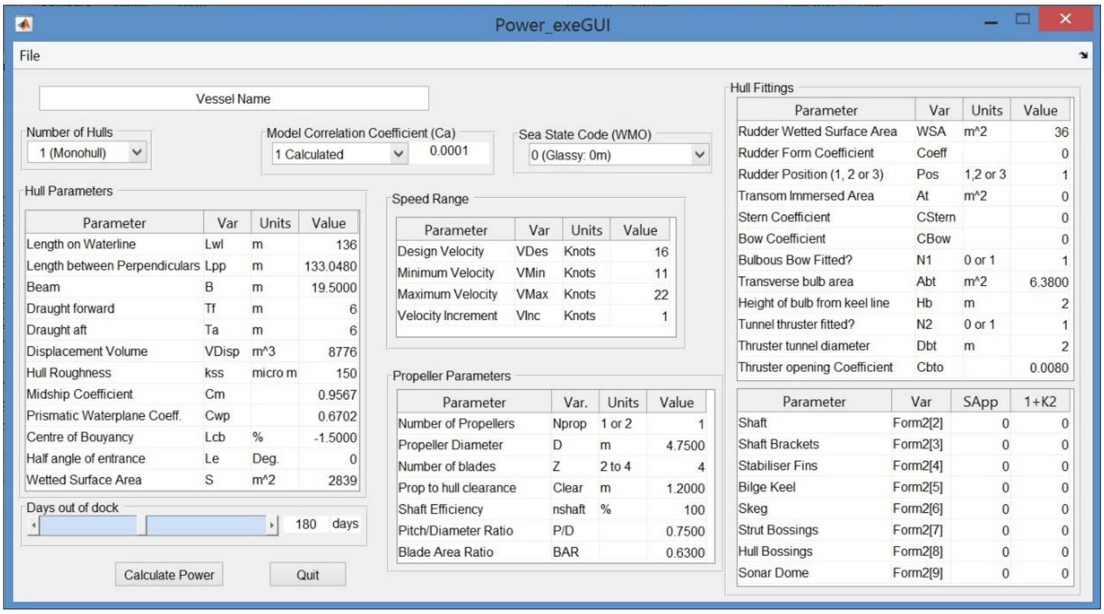

Figure 20. Power_exeGUI developed using Matlab GUI.

The GUI facilitated rapid testing of the original code and led to several findings and code modifications, such as:

- A problem in the Theilheimer cubic spline calculation for extrapolating resistance curves beyond the tabled speed range. Moody had used a series of FOR loops in his matrix of Gaussian elimination for solving systems of linear equations. The matrix row swapping code wasn't compiling correctly, so this was amended by changing to a FPC REPEAT…UNTIL loop. As part of this debugging it was found that Matlab has faster solvers for systems of linear equations. The Matlab solution was not implemented, but may be worth future consideration if an improvement in program speed is required.
- Several other problems were amended relating to the conversion from original Pascal code to FPC code, such as the library implementation of "Log" to "Log10", units compilation ("Unit" function) and the original form feed in output files.
- An error in wind resistance calculation, resulting in an 11 kN difference from Moody's published results, was found and amended.
- An error was found and amended in the relative rotative efficiency calculation.

4.2 The little ferry setting a big example in urban river transport

Over the past 12 months, Australian politicians have been endorsing plans for one of the largest coal mines in the world,[129] while the Great Barrier Reef is being damaged by recurrent bleaching events due to global warming.[130] In contrast to this disturbing mix of climate change denial and evidence on Australia's east coast, an all-electric ferry has been sparkling like an Argyle diamond on Australia's west coast. The 11-passenger, all-electric ferry, "Ellie J" (Figure 21) has been operating for over 12 months on the Swan River in Perth, Western Australia.

Figure 21. The "Ellie J" all-electric ferry in Perth, Western Australia. Photo courtesy of Little Ferry Company, https://www.littleferryco.com.au.

The "Ellie J" operates from mains electrical energy stored in 21 kWh of lithium-ion batteries. The vessel also has 1.6 kW of solar panels on its roof that provide up to 35% of its energy requirements.[131] The vessel is propelled by two 4 kW electric outboard motors.

During sea trials of the vessel (Figure 22), it achieved 7.3 knots at full power. Most impressively, it can cruise at up to 4 knots on solar power alone.

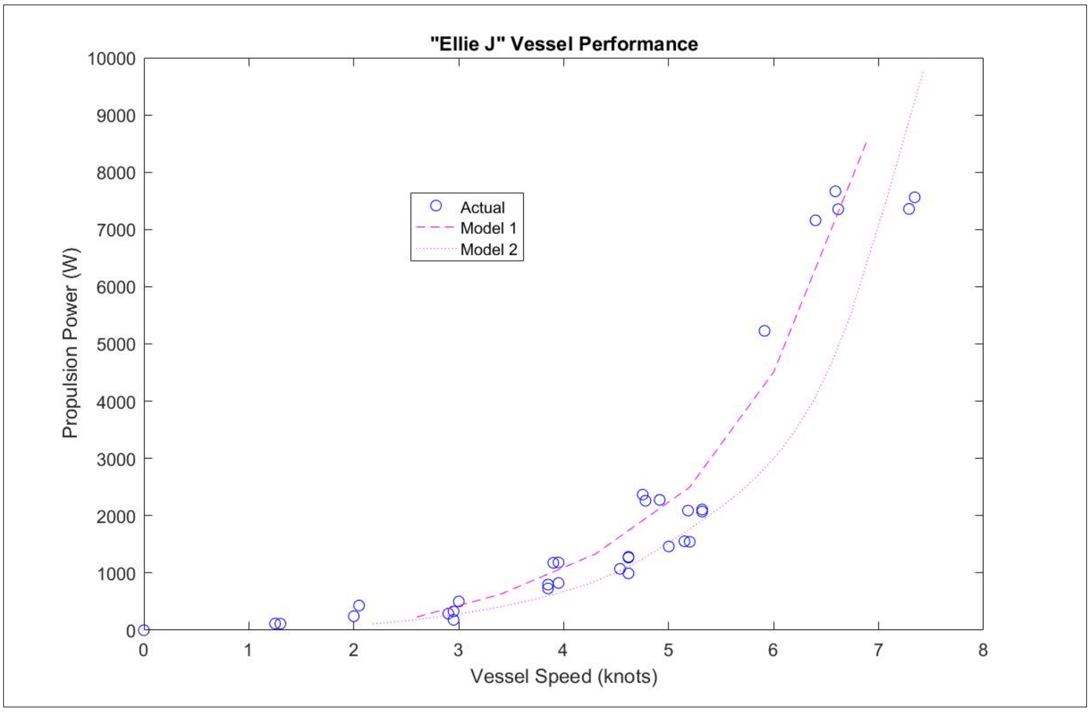

Figure 22. “Ellie J” Vessel Performance.

A top speed of 7.3 knots may not impress boat racing enthusiasts, but it is ample for ferry routes on the Swan River near Perth’s CBD, where the speed limit is 8 knots in most areas and drops to 5 knots near bridges and quays. A feature of this ferry that sailing enthusiasts would appreciate, is its lack of engine noise. Passengers can converse at normal levels, needing only to compete with the sound of water lapping against the hull. Unlike diesel ferries that envelop passengers and bystanders in clouds of diesel exhaust as they accelerate from jetties, the “Ellie J” slips quietly away with no emissions at all.

Perth’s Little Ferry Company[132] has demonstrated that electric propulsion is viable for short-run ferry routes and the company has recently launched an identical sister ferry, the “Jessica Leigh”. Importantly, these ferries are showing that the public is keen to support quiet, low-emissions transportation. For example, Little Ferry Company’s ferries were rated by TripAdvisor in April 2017 as #3 out of 178 things to do in Perth and in May 2017 as #1 out of 25 Boat Tours & Water Sports in Perth.[133]

The International Maritime Organisation (IMO) MARPOL Annex VI Regulations, the Paris Agreement (COP21) in 2015 and the pending Norwegian ban on internal combustion engines[134] clearly indicate that vessel operators need to be considering fuel efficiency and SO_x, NO_x, CO_2 and particulates emissions. Electric propulsion has been used since the early 20th century in niche applications such as submarines, cruise ships and ice-breakers. Electric propulsion with battery storage is an important enabler for improved fuel efficiency and reduced emissions, by facilitating increased use of shore electrical power and solar PV.

Early problems with lithium-ion battery technologies are being overcome and their use is increasing for energy storage due to superior energy density compared to older battery technologies.[10] In the past decade the combination of electric propulsion and energy storage has been used to provide fuel savings and emissions reduction in new electric ferries.

European ferry operators were first to demonstrate the operational savings of marine electric propulsion, by completely replacing diesel fuel with mains electricity and solar energy. The "Ar Vag Tredan" ferry in France was the first in the world to use shore electrical power stored in super-capacitors.[3] The all-electric car ferry "Ampere" uses shore electrical power and lithium-ion batteries and commenced operation in Norway in May 2015. With the change from diesel propulsion to battery, ship operator Norled has reduced their cost of fuel by 60 percent.[4]

Importantly, the "Ar Vag Tredan" and the "Ampere" are made of aluminium. The "Ampere" is only half the mass of a similar sized steel ferry and has double the expected hull lifetime.[4] This has important implications for Australia, because the country is the world leader in aluminium shipbuilding. Australian aluminium shipbuilders built more than 70% of the world's contracted high-speed aluminium vessels in 2008 and one of those shipbuilders, Austal, is contracted to manufacture 15% of the US Navy's fleet.[12] Endorsement of high-efficiency vessel exports could be a more useful endeavour for Australian politicians than thermal coal exports.

Short-run passenger ferry routes in metropolitan areas is an ideal application for electric propulsion with battery storage, due to the close proximity of mains electricity and the need to reduce SO_x, NO_x and particulates emissions. The "Ellie J" has demonstrated the market for these vessels in Perth and indeed in all cities with navigable rivers. The path is clear for operators to apply electric propulsion for improving metropolitan air quality while impressing customers and achieving significant operational savings.

4.3 Modelling Software Development

The completed modules of the electric propulsion model are highlighted in blue shading within a plan for a comprehensive MEP system model in Figure 23.

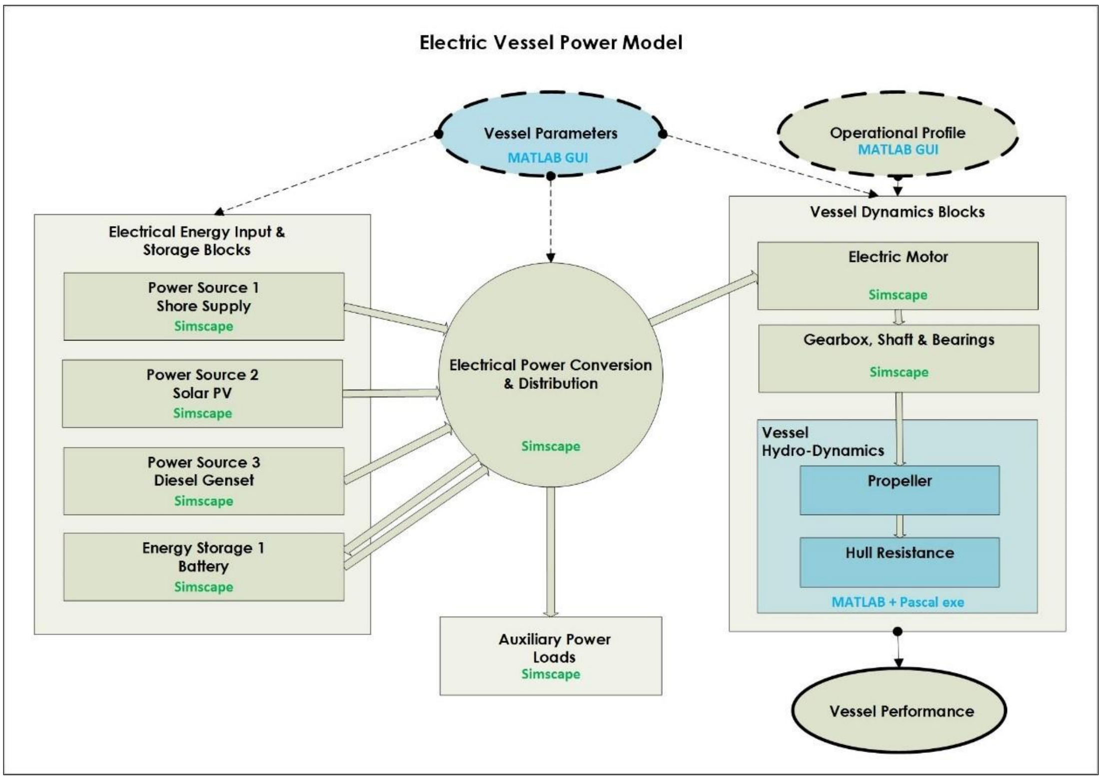

Figure 23. Software development progress (shaded blue) towards a full MEP model.

4.4 Model comparison with “Ellie J” performance

Appendix A provides a detailed comparison of the modelling methods applied in this project.

Power versus speed was determined for “Ellie J” from:

1. Maxsurf Holtrop data,
2. Oceanvolt spreadsheet calculations (based on other actual electric vessel performance),
3. The Matlab model (based on Moody’s preliminary power estimating program) and
4. “Ellie J” sea trial data.

These are plotted on the same axes in Figure 46 in Appendix A.

All three models fit the measured data closely. As expected, the Maxsurf Holtrop data was ‘optimistic’, as it does not consider propeller efficiency, topside wind resistance, or sea state.

The Oceanvolt spreadsheet data was more ‘realistic’ than the Maxsurf Holtrop data or the Moody model, as the spreadsheet is based on actual performance data from previous new-build electric vessels.

Two conclusions were drawn regarding the difference between the Moody model and the Oceanvolt spreadsheet model:

1. The Moody model uses B-Series propeller data. The actual “Ellie J” propeller efficiency could be better than the B-Series estimates at higher speeds, which would explain the Moody model slope being steeper above 6 Knots. With its strong basis in real-world data for similar-sized hulls and propellers, the Oceanvolt spreadsheet provides a better model than the Moody model for the case of calm water and no wind. As suggested in section 4.1, the choice of Wageningen B-screw Propeller Series rather than Gawn Series should be reviewed for Marine Electric Propulsion modelling, as Gawn Series handle a larger P/B range and pitch diameter range than B-series and most propellers currently in use for electric propulsion have three blades.
2. An estimated shaft efficiency of 70% was used in the Moody model, considering that each outboard motor on “Ellie J” consists of a pod-mounted motor and gearbox. The Oceanvolt spreadsheet calculates ‘Pbatt’, or power at the battery, which would include losses in the electric motor, gears and the power electronics.

The Oceanvolt spreadsheet closely approximates vessel performance, despite using only four input parameters. This compares with the Moody model requiring at least 25 input parameters for a calm sea estimate.

4.5 Modelling Conclusions

The advantage of the Moody model, compared to the commercial spreadsheet, is its ability to estimate:

- Wind speed and wind resistance based on sea state.
- Added resistance due to sea state (waves).
- Appendages’ resistance.
- Hull fouling resistance.

While not essential for short-route river ferry applications, these parameters will be relevant for applications where estimates of range and sea-state performance are required for ocean-going vessels. These are also important considerations for ensuring that an ocean-going vessel design will satisfy the IMO’s Energy Efficiency Design Index (EEDI) for new ships and in particular, that the vessel will meet powering requirements for a Beaufort sea state of

6, as required by the IMO guidelines for calculating the coefficient f_w for the decrease in vessel speed in a representative sea condition (MEPC.1/Circ.796). [135]

The following steps should be considered for further development of modelling software based on the Moody methodology:

1. Replace the Wageningen B-screw Propeller Series with the Gawn Series for estimating propeller open-water efficiency and rate of rotation. The Gawn series will be able to handle a larger P/B range and pitch diameter range, considering that most propellers in use for electric propulsion have three blades.
2. Adapt and test the model for catamaran and trimaran hulls.
3. Supplement the Gawn Series with models for propeller operation in two additional quadrants: reversing and sail regeneration.
4. Add models for vessel electrical sub-systems, including:
    a. Solar PV sub-system model;
    b. Electric motor and (optional) gearbox models;
    c. Electrical power conversion and distribution;
    d. Battery and (optional) super-capacitor models; and
    e. Auxiliary electrical loads model.

Chapter 5: Solar PV for Marine Electric Propulsion

5.1 Overview of Chapter 5

The use of solar PV on vessels is constrained by two issues:

1. As identified in Chapter 2, there is an impression advocated by some in the marine industry that solar PV is only useful for providing auxiliary power on vessels.
2. As found during the MEP modelling described in Chapter 4, there is also a lack of established design guidelines for application of solar PV to vessels.

In order to challenge assumptions about the usefulness of solar PV on marine vessels, section 5.2 explores two relevant quotes by Tesla CEO Elon Musk about the limitations of solar PV use in electric vehicles. Section 5.3 then develops a strong counter-argument for the use of solar PV in marine vessels. The novel “Mean Feasible Power by Solar”, or MFPS index, is developed to estimate the feasible contribution of solar PV energy to a vessel’s propulsion.

Sections 5.4 and 5.5 describe the development of a prototype solar PV system used to explore design factors and energy yield of current PV technology.

5.2 Solar PV use in transport

Elon Musk, CEO of Tesla and SpaceX, made the following statement about solar energy in an address to the US state governors at the NGA conference in July 2017, [136]

> *So first of all, it's important to appreciate that the earth is almost entirely solar-powered today, in the sense that the Sun is the only thing that keeps us from being at roughly the temperature of cosmic background radiation - which is three degrees above absolute zero. So if it weren't for the Sun, we'd be a frozen dark ice ball. The amount of energy that reaches us from the Sun is tremendous. It's 99 percent-plus of all the energy that the Earth has. Then there's this energy we need to use to run civilization, which to us is big but, compared to the amount of energy that reaches us from the Sun, is tiny. So it's very easy, actually, it doesn't take much. If you wanted to power the entire United States with solar panels it would take a fairly small corner of Nevada, Texas, Utah ...anywhere. You only need about 100 miles by 100 miles of solar panels to power the entire United States. And then the batteries you need to store that energy, to make sure you have 24/7 power, is one mile by one mile. One square mile - that's it. I've showed the image of this, where this is what 100 miles by 100 miles looks like: a little square on the US map. And then there's a little pixel inside there and that's the size of the battery pack that you need to support that - real tiny.*

Elon Musk advised later in his address that electric vehicle energy requirements are not easily met by on-board solar energy: [136]

> *Putting solar panels on the car itself - not that helpful, because the actual surface area of the car is not very much and cars are very often indoors and so the least efficient place to put solar is on the car. I've really thought about this and I really pushed my own team about this, like: "Isn't there some way we could do it on the car?" I mean, technically, if you have like some sort of transformer-like thing, which will pop out of the trunk like a hardtop convertible and just ratchet solar panels over the whole surface of the car, extending this for the entire square footage of a parking space. Provided you're in the sun - that would be enough to generate about 20 to 30 miles a day of electricity. But that is for sure the expensive, difficult way to do it.*

This is no doubt correct for the majority of passenger cars that commute in cities, nevertheless the annual solar car challenge in central Australia demonstrates the increasing capability of solar-powered cars designed for operation on highways.

Not all marine transport applications will be feasible for 100% on-board solar powering, but some will be.

5.3 Maximum Feasible Power by Solar (MFPS)

Remember that in Section 2.2 it was stated:

> *It should be remembered in context that 1 kW/m^2 peak solar irradiance onto 18% efficient solar panels would generate a maximum of 9 kW from a 50 m^2 (10 m x 5 m) array on a 15 m length vessel, excluding any further system losses. Therefore solar PV panels can only provide auxiliary power or a small proportion of the propulsion power of a commercial vessel in continuous operation.*

This view was influenced by the reviewed literature, particularly the UK Royal Academy of Engineering's report "Future Ship Powering Options",[28] which claimed:

> *Photovoltaic methods offer an approach for limited amounts of power generation on board ships and trials have demonstrated that some benefit is available for auxiliary power requirements. However, the maximum contribution is small when compared with the power required to drive the ship (Mackay 2011).*

In the executive summary it further stated:

> *Renewable energy, principally derived from wind and solar origins, is considered as an augment to the main propulsion and auxiliary power requirements of a ship.*

The fact that "MS Turanor PlanetSolar" circumnavigated the globe in 2012 using only solar energy[1] runs counter to this view. This incongruity warrants further investigation.

The "MS Turanor PlanetSolar" is an exemplar for a 100% solar-powered vessel. Comparing this to Elon Musk's solar-powered EV template - limited by the area of a car parking space to 30 miles a day - suggests that on-board solar power will be more readily applied to ships than to cars, because ships are not restricted to the square footage of a car parking space. Furthermore, ships on open water and within ±30° latitude from the equator are not subject to direct shading from ground-based objects.

The demonstration in 2012 of a 100% solar-powered vessel benchmark enables estimation of the proportion propulsion power that can be provided by a solar PV system. This estimation of feasibility would be a useful tool during the preliminary design of high-efficiency vessels.

The key data for a representative set of vessels was collected and is shown in Table 2.

Vessel Name	Type	Launched (Year)	Waterline Length (m)	Max Beam (m)	Installed Propulsion (kW)
Hormuz	Aluminium Catamaran MDO fast ferry	2007	61.1	16.5	26000
Harmony of the Seas	Steel Monohull passenger MDO cruise ship	2016	330	66	60000
Bhagwan Dryden	Aluminium Catamaran MDO work boat	2014	55.8	16.4	1500
MV Hallaig	Steel Monohull diesel-electric ferry	2012	43.5	12.2	750
Future of the Fjords	Carbon Fibre Catamaran all-electric Ferry	2018	42.5	15.2	900
Wavedancer III	Fibreglass Sailing Catamaran, diesel hybrid	1986	30	12.3	440
Majistic II	Aluminium Catamaran diesel ferry	2001	34	13.5	448
Ar Vag Tredan	Aluminium Catamaran all-electric ferry	2013	22.1	7.2	150
Solar Albatross	Fibreglass Catamaran, solar, diesel ferry	2011	24	6	90
Ampere	Aluminium Catamaran all-electric ferry	2014	78.6	21.4	900
Ellie J	Wooden Monohull all-electric ferry	2016	7.6	2.5	8
Energy Observer	Fibreglass Catamaran, all-electric, solar	2016	30.5	12.8	82
Kato	Carbon Fibre sailing & electric Catamaran	2017	19.5	8.6	30
MS Turanor PlanetSolar	Carbon Fibre Catamaran, solar powered	2010	31	23	120

Table 2. Key vessel data for feasible solar PV calculations.

The maximum solar PV power that could feasibly be generated on a vessel of known length, beam and installed propulsion power was estimated as follows:

1. The area of a rectangle approximately the length and width of the "MS Turanor PlanetSolar" is calculated (Waterline Length x Maximum Beam).
2. This rectangular area (713 m^2) is then divided by the published solar PV area of "MS Turanor PlanetSolar" (512 m^2), to get a topside PV area reduction factor for the vessel of 0.7181.
3. If it is assumed that the installed propulsion power of "MS Turanor PlanetSolar" (120 kW) is approximately equal to the peak power of the solar PV system, a

theoretical efficiency figure can be derived for the vessel's solar PV and electrical system. This theoretical efficiency of 0.2343, or 23.4% is impractically high, considering (a) realistic system losses and (b) average commercial PV cell efficiencies in 2010 were 15% (see Figure 1 on page 8). However, if it is assumed that the vessel was designed for continuous solar operation at 70% of the installed propulsion power rating, a more realistic solar system efficiency (for a high-specification vessel) of 0.1640 or 16.4% is obtained.

4. If it is assumed that the vessel operates in the region ±30° latitude from the equator and that solar energy yield is at the peak solar irradiance available at noon in clear weather, of around 1 kW/m^2.[21] This conveniently converts the solar system efficiency of 0.1640 into a dimensioned figure of 0.1640 kW/m^2.
5. In 2018 the "MS Turanor PlanetSolar" installation is a feasible upper limit for a solar PV installation on a vessel. With the estimates for (a) topside PV area reduction factor, (b) PV system efficiency and (c) 70% of installed power rating, the waterline length (L_{wl}), maximum beam (B_{max}) and installed propulsion power (P_b) can be used to calculate a maximum feasible power by solar (MFPS), as a percentage or index of propulsion power, for any vessel.
6. The equation then is:

$$MFPS = \frac{0.7181 \times 0.1640 \times (L_{wl} \times B_{max})}{P_b} \qquad \left(\frac{kW \times m^2}{m^2 \times kW}\right)$$

This reduces to

Equation 1: $$MFPS = \frac{0.1178 \times (L_{wl} \times B_{max})}{P_b}$$

MFPS values for the vessels listed in Table 2 were calculated and are shown in Figure 24.

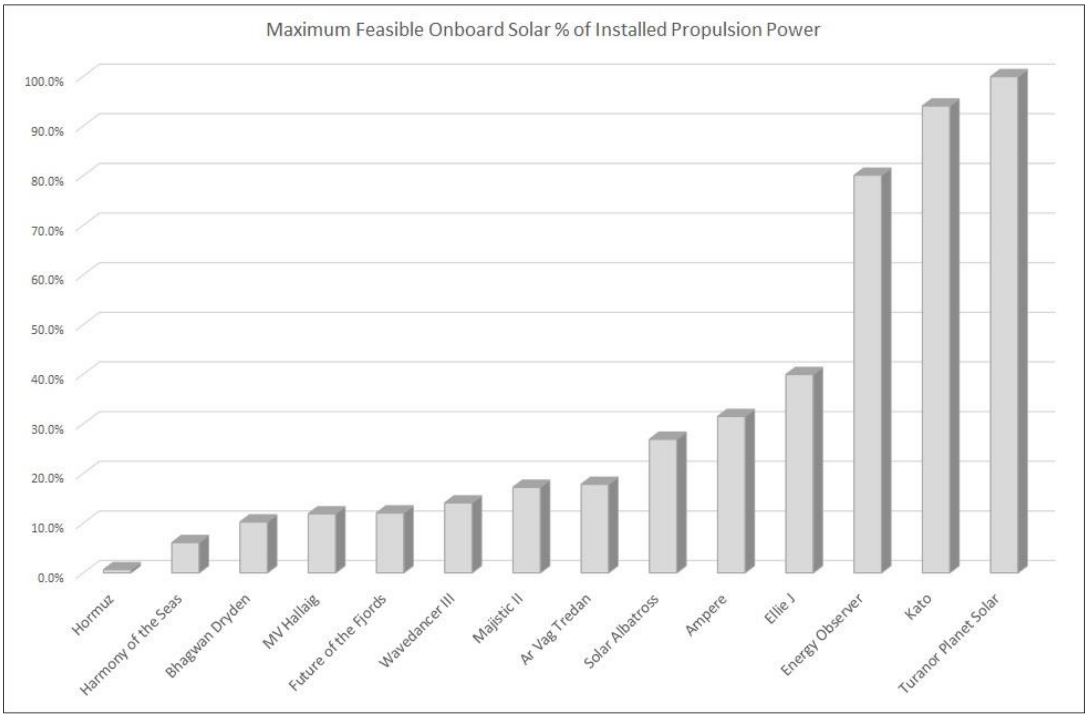

Figure 24. Maximum feasible power by solar (MFPS) as % of rated propulsion power for a selection of vessels (Table 2), relative to "MS Turanor PlanetSolar" = 100%.

There are a several points to highlight in Figure 24:

- The MFPS is a theoretical maximum and takes no account of a vessel's suitable topside space, shading from superstructure/sails, or energy storage. It is also assumed that the vessel's hull and propulsion are appropriately designed, i.e. that the vessel is not over- or under-powered for its application and required speed.
- "MS Turanor PlanetSolar" (MFPS = 100%) and "Kato" (MFPS = 94%) were both rigorously optimised for low weight and propulsion efficiency.[1, 7] For example, both vessels are made of carbon fibre.
- It might be assumed that vessels with MFPS over 20% will be small and very slow, however:
    - "Ampere" (MFPS = 31.5%) is nearly 80 metres in length and carries up to 360 passengers and 120 cars (DWT 199 tonnes). It has a service speed of 10 knots and a top speed of 13.6 knots.
    - "Kato" (MFPS = 94%) reached 9 knots on electric propulsion in shallow water during sea trials in May 2017.
- "Ellie J" is a wood/composite monohull ferry with solar panels covering most of its roof and a published solar PV contribution of 35%.[131] This is consistent with its theoretical MFPS of 40%.
- "Harmony of the Seas" (MFPS = 6.1%) is currently the largest passenger cruise ship in the world.

- "Hormuz" (MFPS = 0.7%) is the fastest diesel-powered vehicle and passenger ferry in the world.
- The majority of large monohull and high-speed catamaran ships in operation in 2017 lie in the region between "Hormuz" (MFPS = 0.7%) and "Bhagwan Dryden" (MFPS = 10.3%).

Solar PV panels can only provide auxiliary power or a small proportion of the propulsion power of <u>most existing</u> commercial vessels in continuous operation. The MFPS index calculated using Equation 1 provides a simple method to determine the feasible contribution of solar PV energy to a vessel's propulsion. This index can provide a useful benchmark during preliminary design of high-efficiency vessels.

5.4 Solar PV system design methodology

Solar PV technology was used initially for remote power applications, including spacecraft and telecommunications sites. The technology has been used for auxiliary power on cruising sailboats for more than 30 years. Growth in solar PV technology use in other marine applications has been relatively slow in the past 20 years, when compared with the growth in fixed systems for residential, business and grid applications.

The exploration of solar PV system performance necessitated development of a prototype. While the marine application of solar PV technology would suggest a developmental system should be installed on a ferry or a ship, these systems are generally located away from land-based meteorology infrastructure. Measuring calibrated meteorological data – particularly insolation – on a moving vessel is a significant problem. Meteorology stations are important to enable accurate baselining of the PV system against measured daily insolation. However, if the prototype was a fixed PV system installed on land, it would limit the system to the conditions at the installation site. The opportunity arose during the project to design and install a solar PV battery charger on a shunting locomotive. This had the combined benefits of (1) close proximity to two BOM weather stations, and (2) a moving platform that could provide data for a range of shading scenarios.

The design methodologies for fixed solar PV systems are well established and a recommended reference is "Planning and Installing Photovoltaic Systems".[21] This reference was used as the basis for the design and installation of the prototype solar battery charger on the shunting locomotive. The shunting locomotive was a useful moving platform for investigating solar PV system design for marine vessels due to:

- Similar topside space restrictions.
- The shunting locomotive was often parked under a shade sail, creating similar solar panel shading conditions to that of sailing vessels and other vessels with significant superstructure.
- The shunting locomotive operates within 3.5km of two Bureau of Meteorology (BOM) stations providing accurate daily insolation measurements and weather data.

The solar energy yield of the locomotive solar charger was estimated using established methodologies. Real world data was logged, analysed, compared with BOM data and then the results used to develop methodologies applicable to marine vessel solar PV system engineering design.

While the design methodologies are well established, the significance of various design decisions to the performance of solar PV systems is not as well understood. The significance of factors such as relative performance and cost of system components has changed with development of new technologies. For example, less expensive PV technology available in flexible formats means that the options for PV placement on vessel topsides are increased. The development of Maximum Power Point Tracking (MPPT) solar charge controllers means less solar energy is lost in the electrical system. By establishing a calibrated measure of insolation into an installation, the relative significance of design decisions can be determined.

5.5 Solar PV system performance measurement

The author, along with colleague and fellow electrical engineer, Pat Patterson, received Downer’s 2015 World Environment Day award for an idea to reduce diesel fuel consumption by using solar power to charge batteries when locomotives are idle for long periods. The award was presented by the Queensland Deputy Premier, Jackie Trad in the presence of the CEO of Downer’s Rail division, Ross Spicer. Shortly afterwards, Downer agreed to fund the design and installation of a prototype solar PV battery charger on a shunting locomotive.

Downer Rail’s Maryborough facility completed the design and build of the prototype locomotive solar battery charger in July 2016 (Figure 25). Learnings about solar PV technology gained through this project’s literature review process were applied to the locomotive prototype design. For example:

- Two high-efficiency (23% cell efficiency/16.8% panel efficiency), flexible, 137 W solar PV panels developed by Solbian for marine applications were used. Flexible panels don’t have an aluminium edge like rigid panels, which prevent water run-off and collect dust at mounting angles close to horizontal.
- The solar PV panels were installed on a stainless-steel mounting sheet to provide heat conduction, and with an air gap to provide air cooling for improved efficiency (Figure 26).
- The solar PV panels were attached to the stainless steel sheet using a grid pattern of 25mm double-sided tape squares, to provide a second (~3 mm) air gap for further thermal isolation. This was suggested by Mr Phil Chapallaz, an electrical engineer and owner of Solar4RVs, based on his own experiment using a simulated RV roof.[137]
- A Maximum Power Point Tracker (MPPT) solar charge controller was used, to ensure optimum capture of solar energy. A further explanation of the advantages of MPPT solar charge controllers is provided in “Planning and Installing Photovoltaic Systems”,[21] section 8.

The installation of this system in July 2016 is believed to be the first solar PV installation on a locomotive in Australia.

5.5.1 Solar PV charger design and installation

Figure 25. Shunting locomotive with prototype solar battery charger (solar panels circled).

Figure 26. Solar Panel Installation

The locomotive solar charger prototype provided an opportunity to collect data on real-world solar PV performance. A problem was identified during the design, whereby solar power can only be measured when there is a load connected: P = V x I, so when I = 0, P = 0. When a solar charge controller detects that batteries are fully charged, it disconnects (open-circuits) the solar panels. If the panels aren't disconnected from the batteries, the excess energy could overheat the battery electrolyte, causing gassing of hydrogen and a reduced battery life. A method was therefore required to enable continued measurement of solar power when the panels were disconnected from the load by the solar charge controller. This problem was discussed with Mr Phil Chapallaz of Solar4RVs. Phil designed and supplied a single-cell solar PV reference cell, with a shunt resistor connected to a Victron Energy BMV702 battery monitor. When connected to a data logger, the solar PV reference cell enables continuous measurement of solar power.

The solar PV reference cell assembly also included a thermistor to enable the logging of cell temperature. Mr Phil Chapallaz advised that a temperature calibration offset was required, “the thermistor supplied by Victron as part of the BMV702 was measured and estimated to be a 200 kOhm thermistor. Therefore a 200 kOhm thermistor has been used for the reference cell. However, there is a systemic error in the temperature measured by the BMV702. The attached Excel spreadsheet provides the calibration. Calibrated temperature = 0.8435 * BMV700 Temperature + 8.02.” This calibration was applied programmatically to the data in the analysis using Matlab.

The reference cell was installed on the locomotive, next to the main panels (Figure 27). The battery monitor and data logger were installed with the solar charge controller inside an equipment box in the locomotive battery compartment.

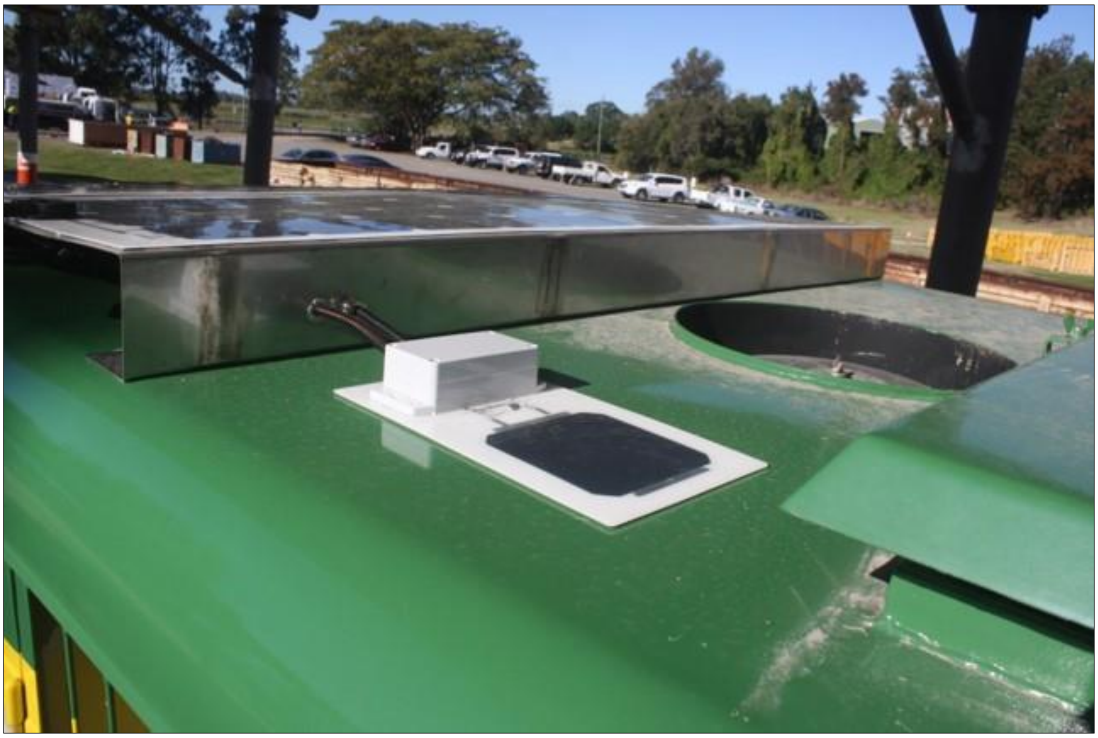

Figure 27. Single-cell solar PV reference cell

5.5.2 Solar PV yield estimation

There are a number of losses in the chain of energy conversion from the sun to battery energy storage:

1. The intensity of solar radiation outside the Earth's atmosphere depends on the distance between the sun and Earth, which varies in the course of a year between 1325 W/m^2 (at 1.52 x 10^8 km) and 1412 W/m^2 (at 1.47 x 10^8 km).[21]

2. Irradiance is effected as it travels through Earth's atmosphere by:[21]
    a. reflection off the atmosphere;
    b. absorption by molecules in the atmosphere (O_3, H_2O [clouds], O_2, CO_2);
    c. Rayleigh scattering (molecular scattering); and
    d. Mie scattering (scattering of dust particles and pollutants in the air).

    This varies during the course of a day due to changes in the atmosphere and changes in the sun's elevation angle relative to points on the Earth's surface. It is assumed that the losses due to these effects at the Earth's surface will be similar for locations that are all less than 3.5km apart. (This assumption will be tested in section 5.5.4 and Appendix B). Therefore, by determining the solar system energy conversion efficiency, the solar charger daily energy yield can be estimated from daily insolation data.

3. There are two panels used on the locomotive solar chargers, providing a total solar capture area of: 2 x (1490mm x 546mm) = 1.637 m^2.

4. The mounting angle of the moving PV panel with respect to the position of the sun in the sky will have an effect on yield. The directionality of solar PV cells is not provided in data sheets. The effective area facing the sun of a flat PV panel changes with the sun's elevation angle. For simplicity, it was assumed during the design that:
    a. The PV technology loss due to non-perpendicular irradiation is minimal; and
    b. The effect of changes in the sun's elevation angle during the day would be averaged by using daily averages of insolation and yield for panels that are close to horizontal.

5. Losses due to direct shading can be greater than 50% during shading of just one PV cell in each panel (see Figure 31).[21] As direct shading has such a significant effect that is complex to model for a moving platform, the estimation can be simplified by

considering only days when the locomotive is parked away from near-end direct shading sources. (The effects of direct shading will be revisited in section 5.5.3.)

6. Solar PV cell or panel efficiency. The advertised cell efficiency of Solbian SP137 panels is 23%. Cell efficiency is measured to a standard prior to installation of the cell into a module and therefore excludes unproductive corners and edges (see Figure 26) and protective coating losses. Panel efficiency is calculated by the formula Output Power/(L x W x insolation power) and assuming that the 137 W nominal power rating per panel is based on the international standard temperature and conditions (STC) of 1 kW/m^2 insolation at 25 °C. This means Solbian SP137 panels have a panel efficiency of 16.8%.

7. As rated panel efficiency is at STC, there is a further loss in the panels due to a reduction in silicon PV performance with increased temperature. Typical temperature coefficients for solar PV panels are published in "Planning and Installing Photovoltaic Systems" and have been reproduced in Table 3.[21]

Typical temperature coefficient	Crystalline silicon modules	High-performance modules (HIT, SunPower)
Open-circuit voltage	–0.30 to –0.55%/°C	–0.25 to –0.29%/°C
Short-circuit current	+0.02 to +0.08%/°C	+0.02 to +0.04%/°C
MPP power (STC)	–0.37 to –0.52%/°C	–0.30 to –0.38%/°C

Table 3. Typical temperature coefficients for solar PV panels, relative to STC.[21]

The Solbian SP137 panels installed in the locomotive solar charger consist of SunPower PV cells[138] and have a data sheet temperature coefficient of -0.38% MPP power per °C of panel temperature relative to STC (25 °C). As Maryborough is located in the subtropics, solar PV panel temperatures are often above STC. The Fraunhofer Institute for Solar Energy Systems (ISE) in 1996 reviewed the solar energy yield in Germany for various PV array installation methods.[21] The ISE findings on temperature increases due to various solar PV panel installation methods are reproduced in Figure 28. The figure also shows the resulting reductions in energy yield due to the temperature increases.

The installation arrangement of the solar panels on the locomotive solar charger (shown in Figure 26) can be assumed to approximate an installation "on/in roof, good ventilation". This would mean, according to Figure 28, an increase in panel temperature over ambient temperature of approximately 29 °C.[21]

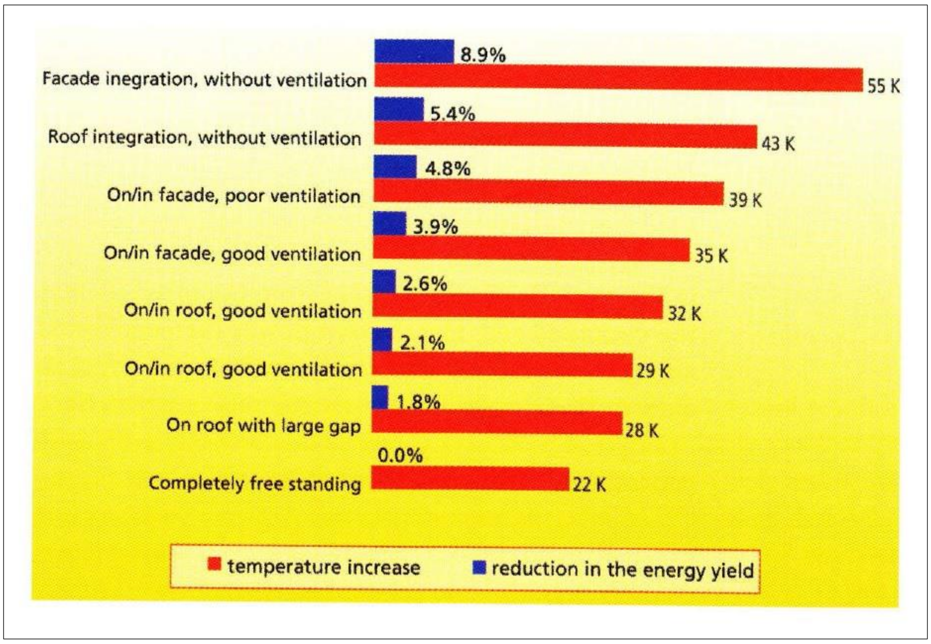

Figure 28. Temperature effect on yield for various PV array installation methods.[21]

The daily peak in solar insolation generally occurs around midday and around an hour before the day's maximum temperature. The BOM provides free online access to historic maximum temperatures for each weather station in Australia and the mean maximum temperatures for Maryborough are reproduced in Figure 29.

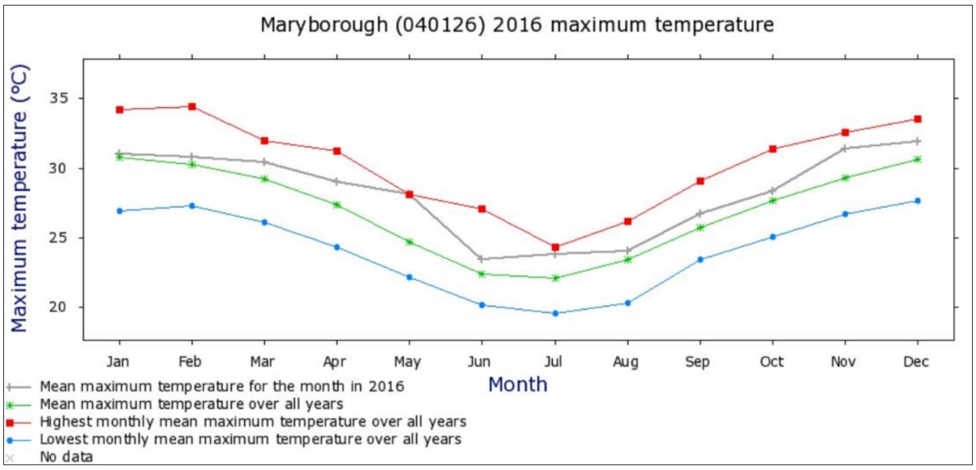

Figure 29. BOM Maryborough mean maximum temperatures.[139]

Figure 29 shows that the mean maximum temperature in Maryborough for every month of 2016 (grey plot) was higher than the long-term mean (green plot). Climate science would suggest that this is symptomatic of global maximum temperatures trending upwards.[130] For estimating purposes during design it is recommended to use the mean of all recorded temperatures, unless accurate projections of climate change are available for the location/s of operation. Climate change temperature projections were not available for Maryborough for this project.

Summing the Maryborough mean maximum temperature with a projected increase due to installation method of 29 °C, gives the estimated monthly mean maximum panel temperatures shown in Table 4. Using -0.38% MPP power per °C of panel temperature above STC (25 °C), gives the estimated reduction in energy yield for Solbian PV panels in Maryborough shown in Table 4.

Month	BOM Mean Maximum Temperature (°C)	Estimated Maximum Panel Temperature (°C)	Estimated Reduction in PV Energy Yield vs STC (%)
January	30.8	59.8	-13.2
February	30.3	59.3	-13.0
March	29.2	58.2	-12.6
April	27.4	56.4	-11.9
May	24.7	53.7	-10.9
June	22.4	51.4	-10.0
July	22.1	51.1	-9.9
August	23.4	52.4	-10.4
September	25.7	54.7	-11.3
October	27.7	56.7	-12.0
November	29.3	58.3	-12.7
December	30.6	59.6	-13.1
MEAN			-11.8

Table 4. Estimated solar PV yield reduction due to temperature in Maryborough.

The estimated reduction in energy yield due to panel temperature of 11.8% in Maryborough is greater than the yield reduction of 2.1% measured by ISE in Germany (from Figure 28), for a similar installation method. This difference is attributable to the difference in ambient temperatures between Maryborough and Germany.

8. The MPPT solar charge controller has a rated maximum efficiency of 98%, which implies a minimum loss of 2%.

9. There are losses in the cables between the solar panels and the MPPT solar charge controller and between the controller and the batteries. These are calculated as follows:
    a. Conductor resistance of 6 mm^2 cable: 3.39 Ω/km
    b. Length of cable (complete circuit): 0.008 km

c. Cable resistance, R: 0.271 Ω

d. Max. current, I (@ min. MPP temperature): 7.9 Amps

e. Cable power loss ($P = I^2 \cdot R$): 1.69 Watts (-0.6%)

The daily solar PV energy output from the solar charger can therefore be estimated for each month, as shown in Table 5.

Month	BOM Mbh[139] Mean Daily Solar Insolation (kWh/m²)	Solar PV Panel Efficiency (%)	Estimated Reduction in PV Energy Yield vs STC (%)	MPPT Solar Charge Controller Loss (%)	Estimated 6 mm² Cable Loss (%)	Estimated Solar Charger Conversion Efficiency (%)	Estimated Mean Daily Energy Output (kWh/m²)
January	6.6	16.8	-13.2	-2.0	-0.6	14.2	0.94
February	5.9	16.8	-13.0	-2.0	-0.6	14.2	0.84
March	5.4	16.8	-12.6	-2.0	-0.6	14.3	0.77
April	4.7	16.8	-11.9	-2.0	-0.6	14.4	0.68
May	3.9	16.8	-10.9	-2.0	-0.6	14.6	0.57
June	3.5	16.8	-10.0	-2.0	-0.6	14.7	0.52
July	3.8	16.8	-9.9	-2.0	-0.6	14.7	0.56
August	4.6	16.8	-10.4	-2.0	-0.6	14.7	0.67
September	5.6	16.8	-11.3	-2.0	-0.6	14.5	0.81
October	6.1	16.8	-12.0	-2.0	-0.6	14.4	0.88
November	6.6	16.8	-12.7	-2.0	-0.6	14.3	0.94
December	6.8	16.8	-13.1	-2.0	-0.6	14.2	0.97
MEAN	5.3					14.4	0.76

Table 5. Estimated solar charger losses and daily energy output.

5.5.3 Effect of bypass diodes and MPPT controllers on solar PV yield

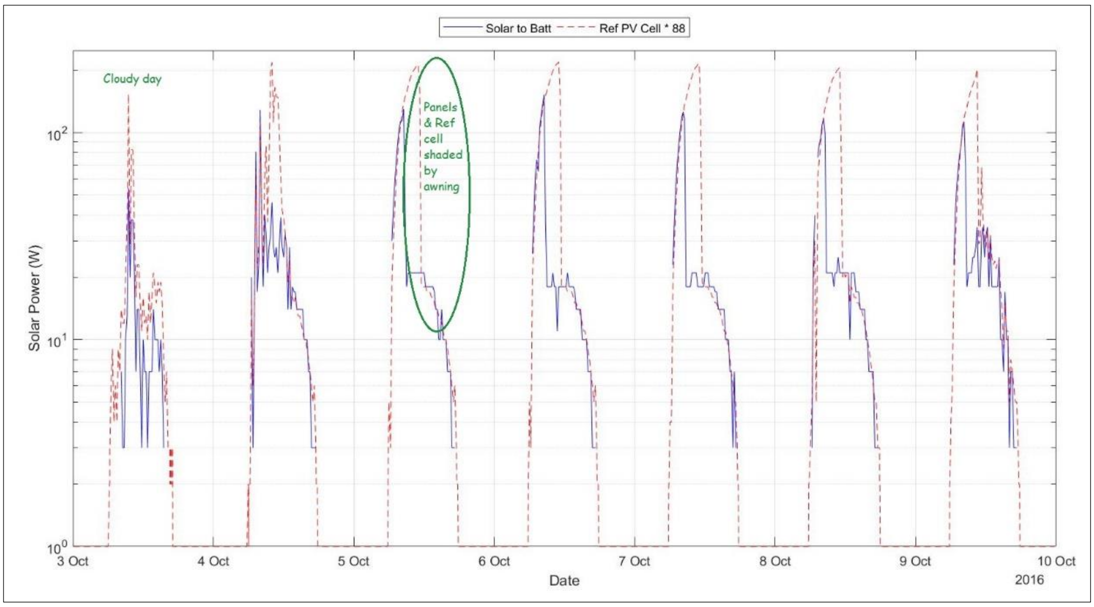

Figure 30. Loco solar charger data, 3 to 10 Oct 2016.

Figure 30 shows a 7-day sample of data obtained from the locomotive solar charger, including power from the main PV panels and power measured by the reference PV cell, multiplied by 88. As the reference PV cell is identical to the cells in the two main solar panels (consisting of 44 cells each), multiplying the single PV cell power by 88 provides a close approximation of the feasible solar power from the installation. It is therefore reasonable to equate the terms “main PV panels power” and “reference PV cell power x 88” to “PV power” in following discussions.

Aside from heavy clouds over which a system designer has no control, direct shading from near-end objects has the greatest effect on solar PV system yield. The shade awning shown in the background in Figure 25, was on the western side of the location where the locomotive was often parked. The awning started shading the western part of the main panels at about 10am, before it shaded the reference PV cell on the eastern side of the locomotive, just before midday. On 5 October 2016, this direct shading resulted in a rapid drop in yield, from around 200 W to 20 W, (a 90% reduction) from the main panels as they became partially shaded at around 10am, as evident in the power levels in Figure 30.

The reduction in yield due to direct shading shown in Figure 30 is similar to shading of panels by sails on a sailing vessel with a constant heading.

The rapid reduction in output power due to partial direct shading is consistent with advice in chapters 2 and 3 of “Planning and Installing Photovoltaic Systems”,[21] which describes how direct shading of just one cell in a panel of cells has a disproportionate effect on the total output power of a panel. The shaded cell not only stops generating current, but becomes a load to the other cells and generates excess heat. This effect is reduced by the use of bypass diodes incorporated into the solar panels, ideally the less PV cells per bypass diode, the better. In practice, due to panel manufacturing constraints, between 10 and 22 cells are connected in series per bypass diode. Solbian SP137 panels have 22 cells per diode.

Because of this common configuration of solar panels, direct shading of only one cell in a panel with (for example) 18 cells per bypass diode, can cause a drop in panel power output (to the green curve) as shown in the typical PV module I-V curve in Figure 31, reproduced from “Planning and Installing Photovoltaic Systems”.[21]

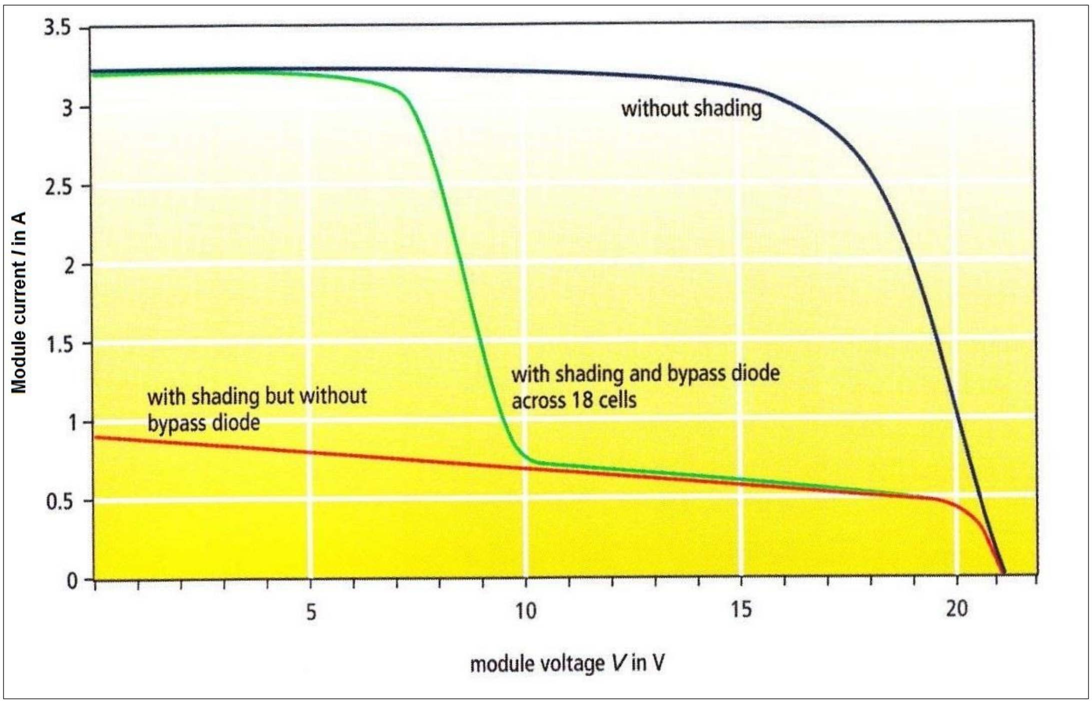

Figure 31. Changes in an 18-cell PV module I-V curve with direct shading of one cell.[21]

A Maximum Power Point Tracker (MPPT) solar charge controller was used in the locomotive solar charger to ensure optimum capture of solar energy. The operation of MPPT solar charge controllers is fully explained in “Planning and Installing Photovoltaic Systems”,[21] section 8. A MPPT solar charge controller will mitigate the effect of direct shading by maximising output power (I·V) as it tracks the green curve shown in Figure 31. For the example shown in Figure 31, even with an MPPT controller in use, with one bypass diode per 18 cells the change is still significant - a drop from 49.5 W to 23W and hence a 53% reduction in panel output power when one cell of the 18 is directly shaded.

The locomotive solar charger PV panel layout was, with hindsight, poorly designed (by the author) for yield during direct shading. The solar charger PV panels were installed lengthwise across the locomotive (Figure 26 and Figure 32).

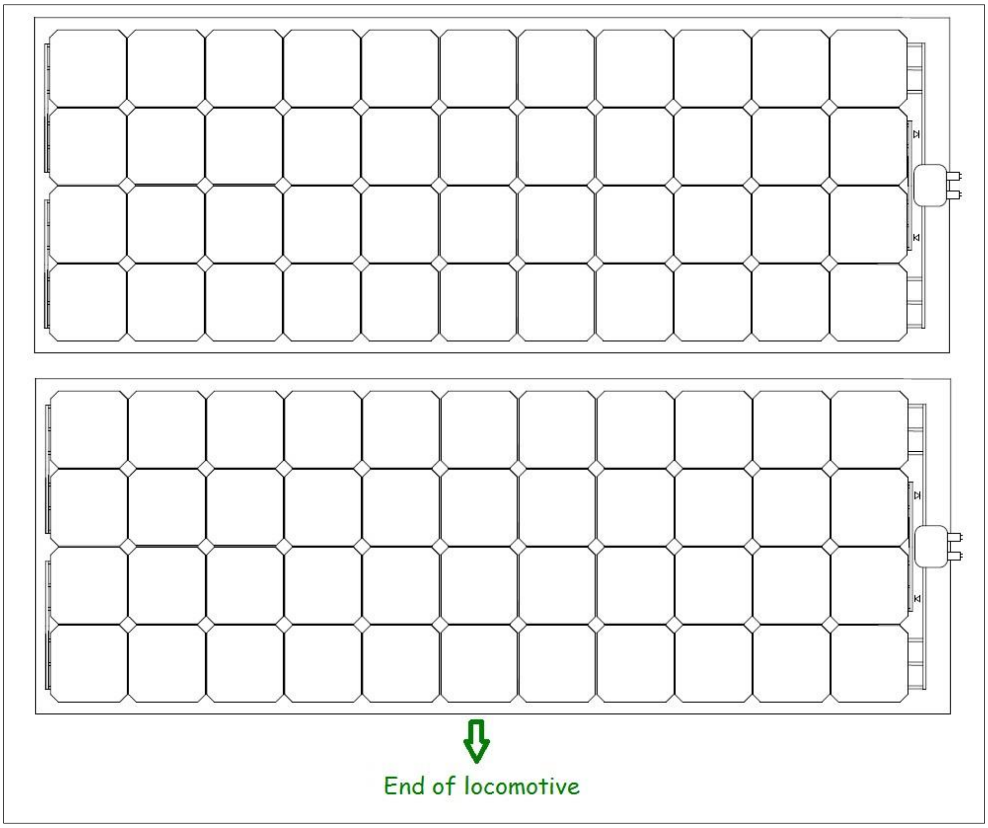

Figure 32. Locomotive solar panel layout with 2 x 44-cell panels and 4 bypass diodes.

This configuration of two long panels and only four bypass diodes exacerbates power reduction due to direct shading. When only one cell in each of the four bypass diode strings is directly shaded, the entire installation is affected. Improved performance in direct shading on all points of the compass could be gained by using four half-sized panels and hence eight bypass diodes, as shown in Figure 33.

Depending on the area available, this may mean that four 20-cell panels (80 PV cells total) replace two 44-cell panels (88 PV cells total) and hence 8 fewer PV cells. Even though the peak power output in full sun will be lower by around 25 W (-9%), this would be offset by significantly better yield during partial direct shading. This counter-intuitive example highlights the importance of considering bypass diode configuration in PV panel layouts. This applies particularly when designing the layout of solar panels for marine solar PV systems where regular shading by superstructure such as masts, booms and sails is likely.

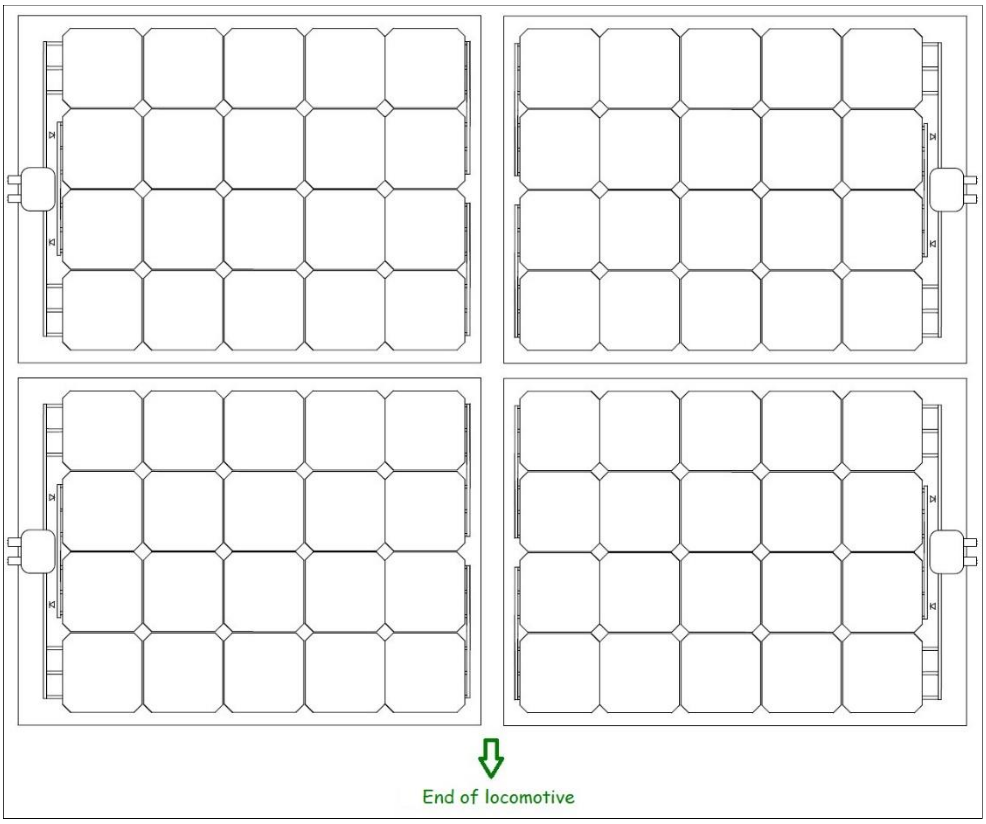

Figure 33. Alternative solar panel layout with 4 x 20-cell panels and eight bypass diodes.

In a vessel with a substantial superstructure, or a sailing vessel with panels shaded directly by mast, boom and sails, two factors will improve direct shading performance:

1. more bypass diodes per panel and
2. a more modular panel layout (smaller, squarer panels) with respect to direct shading.

Investment in electronics topside (ie. the number and location of bypass diodes) is at least as important as investment in electronics below deck (eg. a MPPT solar charge controller).

5.5.4 Bureau of Meteorology data

Bureau of Meteorology (BOM) station location information[139] shows that there are two BOM weather stations in Maryborough, Queensland that measure daily solar exposure (insolation): station 040443 in Maryborough city and station 040126 at the Maryborough airport. A detailed description and analysis of the data available from these two BOM meteorological stations is provided in Appendix B.

Sufficient data was logged by the locomotive solar charger in 2016 and 2017 to identify and quantify the losses effecting its yield. Quantifying these losses and being able to correlate this with two nearby BOM weather stations provided a sound basis for development of a methodology for adapting BOM data to estimates of real world PV power contribution for future applications of solar PV systems.

Based on the details and analysis in Appendix B, it was determined that using the highest insolation level measured at either Maryborough airport station (040126) or Maryborough city BOM station (040433) on each day would reduce the effect of near-end shading obstructions from the BOM daily insolation data. This calculation was included programmatically in the Matlab analysis.

5.5.5 Effect of diffuse irradiance on solar PV yield

An interesting phenomenon of irradiance amplification was noticed in BOM one-minute insolation data and is described in detail in Appendix B.

Diffuse irradiation and the irradiance amplification effect of partial clouding has been described[140, 141] and modelled,[142, 143] however its consideration in the design of marine vessel solar systems has been limited to date. Irradiance amplification has important implications for the design of solar power systems on marine vessels, for example:

- A dome solar PV topology (eg. the shape of a tree in an open field, Figure 34) may be more effective than a planar topology. The optimum topology (eg. height and slope of the dome) may vary depending on the latitude of vessel operation.
- Given two solar PV technology types with equal efficiency at STC, the type that can capture more diffuse irradiance will be more effective.
- Solar PV yield from irradiance reflected from the water's surface (Fresnel reflection) has not been investigated extensively for marine vessel applications. Dammeier et al (2017)[144] measured the contribution of water surface Fresnel reflection on lakeside Building Integrated PV (BIPV) yield. Their model of Fresnel irradiance as a percentage of total yearly irradiance on a vertical surface shows a 5 to 15% contribution, depending on latitude.
- As solar PV prices reduce and coating technologies improve,[10] extensively covering vessel topsides with solar PV may become practical. As this is an extension from BIPV, the appropriate terminology for this would be Vessel Integrated Photovoltaics (VIPV), or Ship Integrated Photovoltaics (SIPV).

Figure 34. A tree in an open field, maximising solar energy yield.

5.5.6 Measured effect of panel temperature on solar PV yield

As shown by the estimated values in Table 4, energy loss due to reduced performance of silicon PV at panel temperatures above STC can be significant: around 13% loss at midday in Maryborough in summer and around 10% in winter. This estimation was based on panels mounted “on/in roof, good ventilation”.

The thermistor in the PV reference cell enabled the estimates of maximum panel temperature (Table 4) to be checked. The measured PV reference cell temperature is plotted against BOM ambient air temperature for Maryborough in Figure 35. The maximum reference PV cell temperature measured on 8 July 2016 at 12:05pm was 46 °C, a difference above STC of +21 °C. Using a temperature coefficient of -0.38% per °C, gives an estimated reduction in peak solar energy yield at MPP of 8.0%. This compares with the estimated mean reduction for July (Table 4) of around 10%.

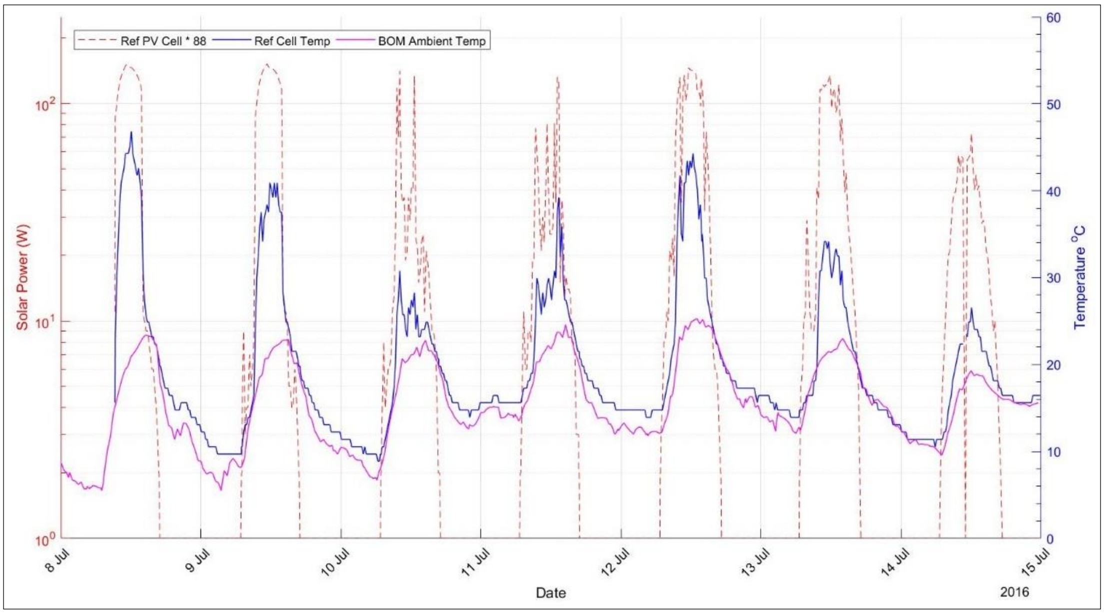

Figure 35. Ref PV cell power (LHS), cell temperature and BOM ambient temperature (RHS)[139], 8 to 14 Jul 2016.

Figure 35 confirms the ISE 1996 findings that solar PV temperature can exceed ambient air temperature by significant amounts due to heating by solar exposure. The solar reference cell was installed on a white polymer backing plate, with double-sided tape insulating it from the locomotive (Figure 27). The air cooling of this configuration may have been different to the solar PV panels which, although adjacent, were installed on a stainless-steel mounting sheet, with an air gap to provide heat conduction and air cooling (Figure 26).

The estimated and confirmed reduction in solar energy yield due to panel temperature, shows that this loss can be significant. The yield reduction that ISE found in Germany was around 2%. Comparing this with an 11.8% average yield reduction in Maryborough for a similar installation method, shows that the reduction will be more significant in subtropical zones than in temperate zones due to higher ambient temperatures. Solar PV cooling should therefore be considered in design of solar PV systems. Further research on this effect, installation methods and viable cooling, as was done by ISE for building applications in Germany, would be beneficial for the design of future marine solar PV installations for vessels operating in subtropical and tropical zones.

5.5.7 Effect of dust and salt crystals on solar PV yield

Given the significant effect on a solar PV panel of direct shading on just one cell, it is important to explore the effects of shading by dust and salt crystals on solar energy yield. The Maryborough BOM insolation data was combined with BOM rainfall data and is shown in Figure 36 for the period 1 July to 30 August 2016.

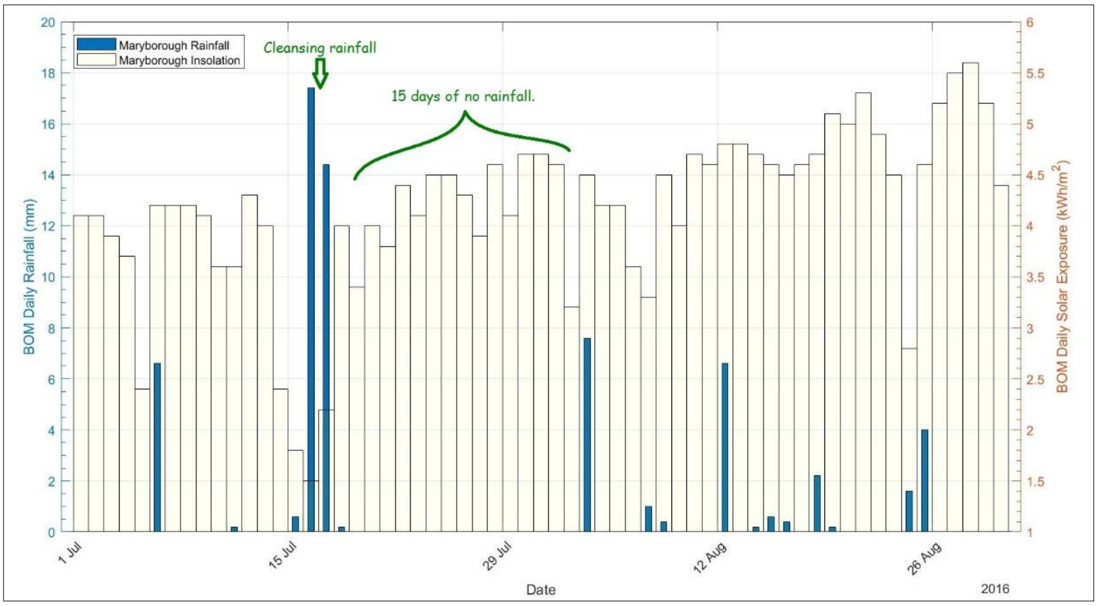

Figure 36. Maryborough daily rainfall and insolation 1 Jul – 30 Aug 2016.[145]

The daily rainfall data is for the previous 24 hours until 9 am on that day. Note the increasing trend in daily solar exposure (excluding cloudy days) as Maryborough, situated in the southern hemisphere, progressed from winter to spring.

Figure 36 shows that there was 6.6 mm of rainfall up to 9am on 6 July 2016, prior to the 8 July photos in Figure 37 and Figure 38. The rainfall on 6 July did not remove all of the dust and caused dust deposits to remain as the rain droplets dried. As the two photos show, the dust build-up was similar on the main panels (Figure 37) and the reference cell (Figure 38).

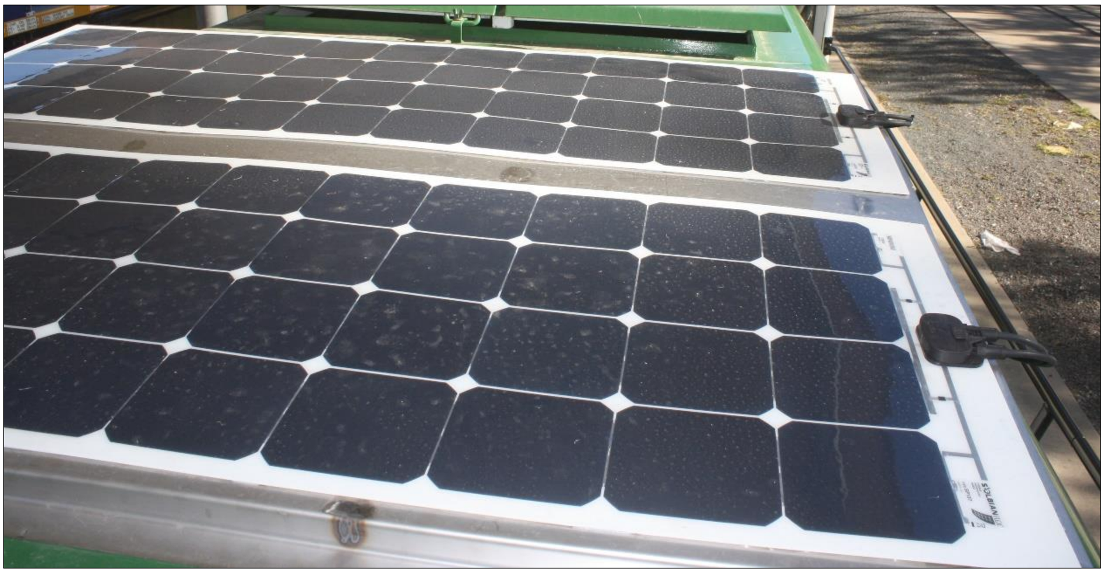

Figure 37. Dust on solar panels after light rain (6.6mm on 6 July 2016), 8 July 2016

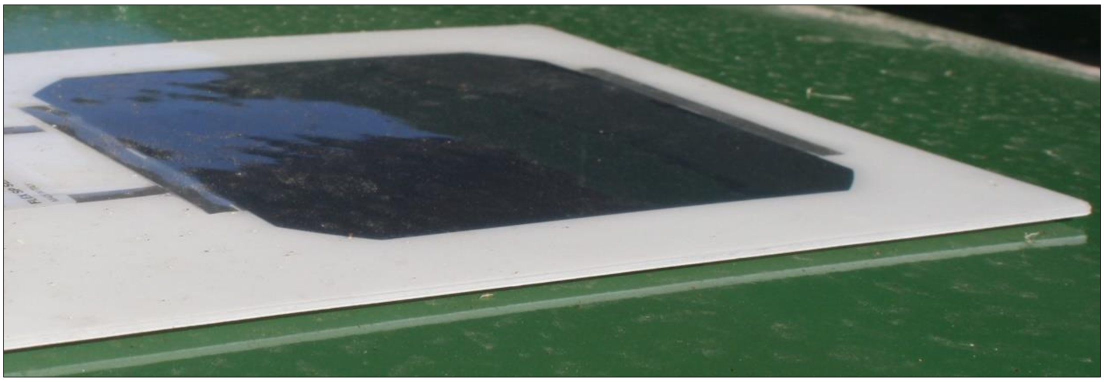

Figure 38. Dust on the reference PV cell, 8 July 2016

As the 6.6 mm of rainfall in the 24 hours prior to 9am on 6 July moved the dust but did not completely remove it, we can search in the BOM data for a more sustained period of rainfall using Figure 36. That occurred on 16 and 17 July, when there was 17.4 mm and 14.4mm respectively. The following 16 days with no rain from 18 July to 2 August 2016, while the locomotive was known to be parked in one location, provides a useful set of data for determining whether dust build-up had a significant effect on solar energy yield.

The locomotive solar charger reference PV cell's daily energy (solar PV energy) was calculated from the solar PV power data using Matlab and is compared graphically with the BOM insolation data in Figure 39. The system daily energy conversion efficiency was then calculated and graphed in Figure 40.

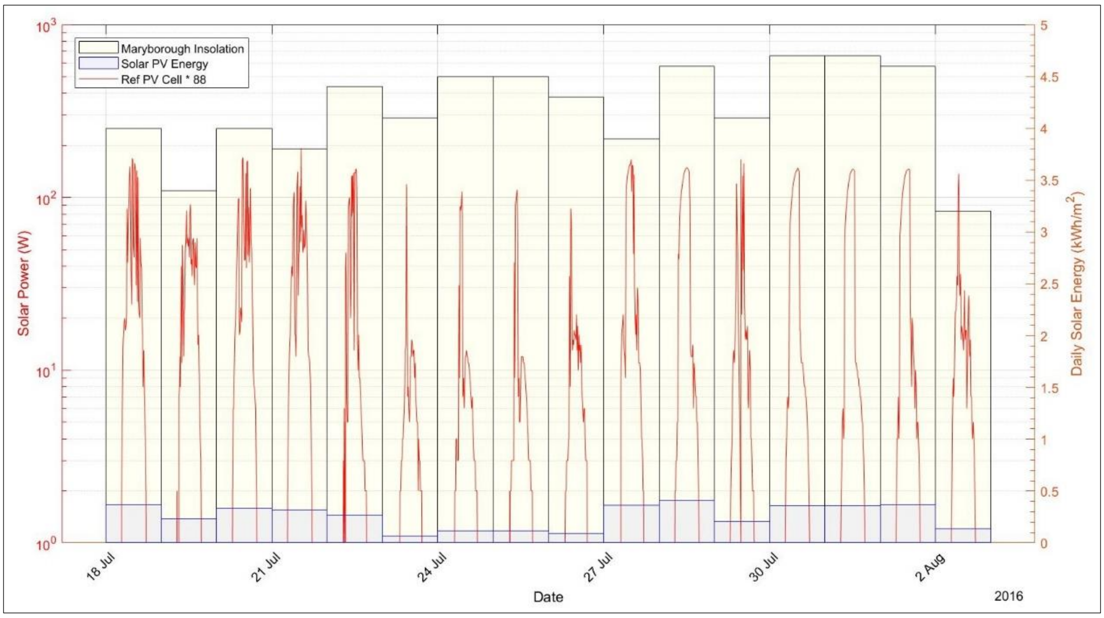

Figure 39. BOM insolation, solar PV energy and solar PV power, 18 Jul - 2 Aug 2016.

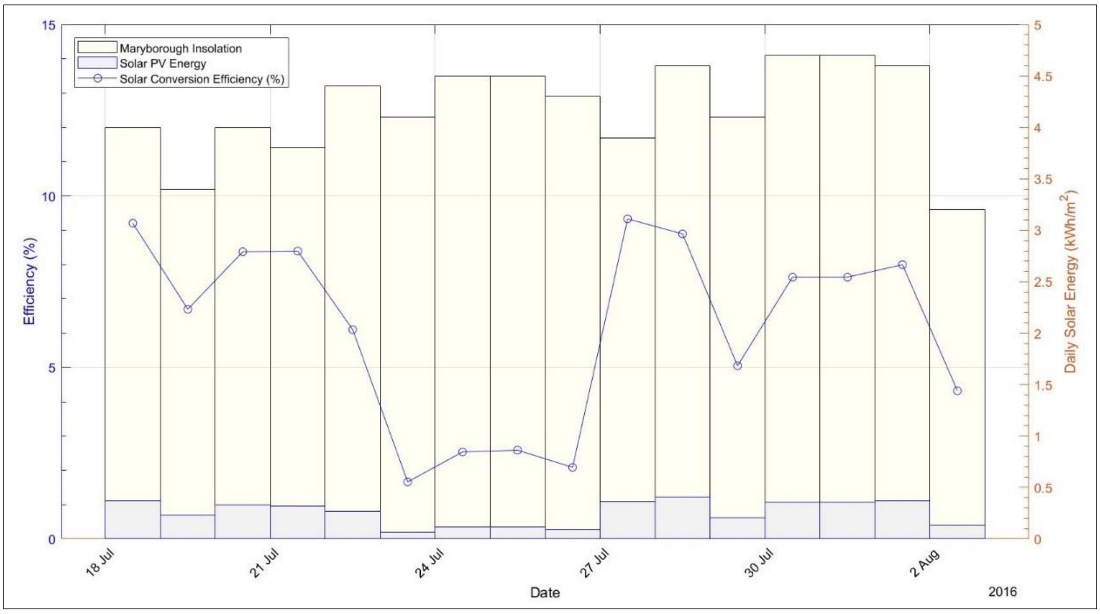

Figure 40. Solar PV energy, BOM insolation and daily energy conversion efficiency, 18 Jul - 2 Aug 2016.

Any significant effect from dust accumulation would appear in Figure 40 as a downwards trend. Unfortunately a clear trend cannot be discerned due to locomotive near-end shading events on 23 – 26 July 2016. We can be confident that this shading was localised at the Downer Maryborough facility, because there was no similar drop or significant discrepancy in insolation measured at the two Maryborough BOM stations on these four days (station insolation was around 4 kWh/m^2 with a difference of < 0.1 kWh/m^2 or < 2.5% per day, see also Appendix B, Figure 49). If we exclude 23 – 26 July 2016 from the analysis, there appears to be a downwards trend of approximately -1% per week.

The cause of the downward trend can be tested by reviewing the original assumption that two days of rain on 16 and 17 July cleaned dust off the panels. By zooming the solar charger daily conversion efficiency plot out to October 2016 and plotting this with the BOM rainfall data - which conveniently fits the same y-axis scale - another significant rainfall event appears in the 12 hours prior to 9am on 3 September 2016, of 18.2mm (Figure 41).

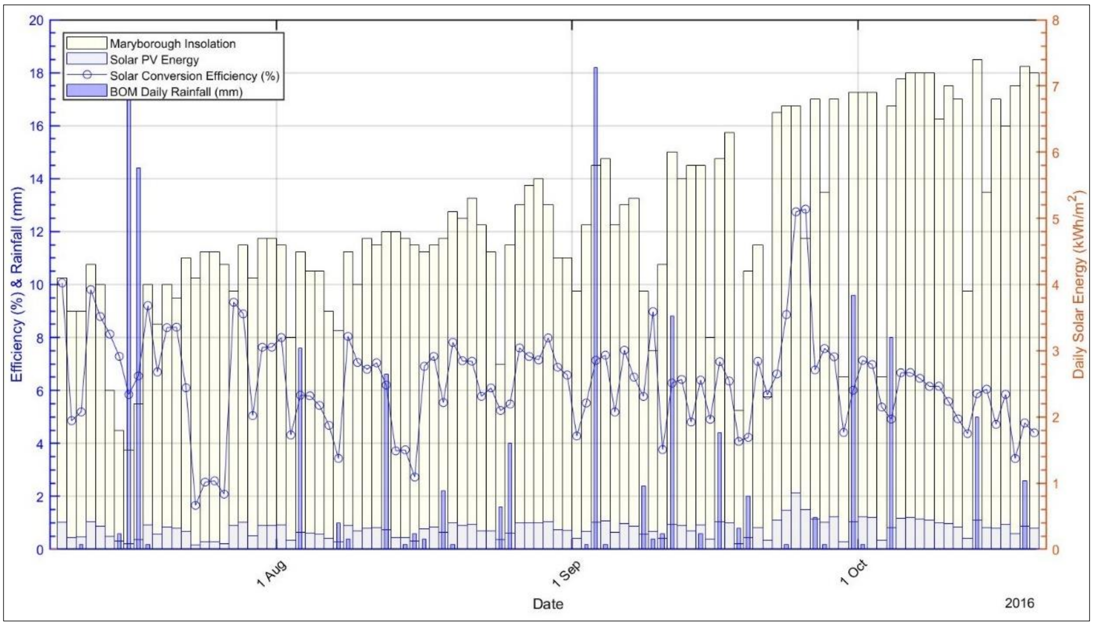

Figure 41. Solar PV energy, BOM insolation, conversion efficiency and BOM daily rainfall, 16 Jul - 20 Oct 2016.

If the original assumption was correct, we would expect to see in Figure 41 a re-bound in conversion efficiency immediately following the rainfall on 3 September 2016. However, there is no change in the downward trend. We can therefore conclude that the effect of dust build-up on solar yield is negligible relative to other shading effects. The downward trend of approximately 1% per week appears to be related to the changing position of shade from the awning (Figure 25) as the seasons progressed. This is confirmed in Figure 41: when the locomotive was moved away from the shade awning on the 24 and 25 September, there was a doubling in daily conversion efficiency, from around 6% to 12.74% and 12.84% respectively.

The negligible effect of dust build-up has implications for solar PV system design for the subtropics. Panels should be sufficiently inclined to shed dust and salt during rainfall. Furthermore, an automated solar panel cleaning system is unlikely to provide sufficient benefit to justify its cost.

5.5.8 Solar PV yield measurements

Since the locomotive was moved to an area with no significant direct shading on the 24 and 25 September 2016, this provides two days of data to test our estimation of solar PV yield. Furthermore, Figure 42 shows that 24 September was a clear sunny day and 25 September was a partially cloudy day.

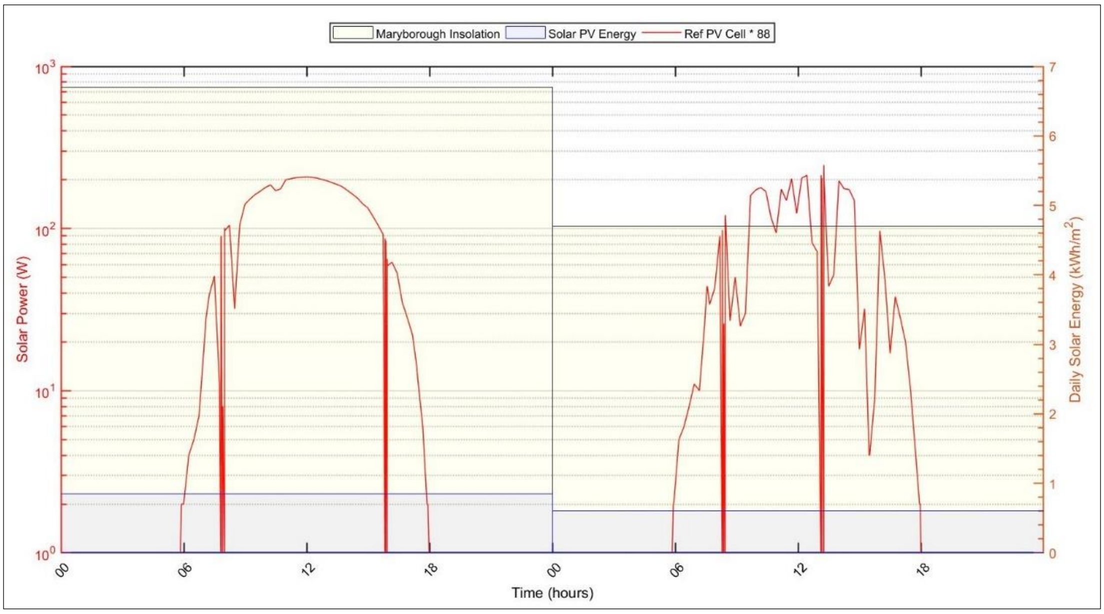

Figure 42. Solar PV power, energy and BOM insolation, 24 - 25 Sep 2016.

A further search for high levels of daily conversion efficiency in available data revealed that the locomotive was also in an area without direct shading on 21 – 27 September 2017. The available 2016 and 2017 data included 9 days where the locomotive solar charger had no near-end direct shading. The 9 days are listed in Table 6.

Date	BOM daily Insolation (kWh/m2)	Solar PV Energy Yield (kWh/m2)	Conversion Efficiency (%)
24 September 2016	6.7	0.854	12.74
25 September 2016	4.7	0.604	12.84
21 September 2017	5.8	0.722	12.44
22 September 2017	5.1	0.479	9.40
23 September 2017	6.4	0.772	12.06
24 September 2017	6.4	0.857	13.40
25 September 2017	6.5	0.801	12.32
26 September 2017	6.6	0.718	10.87
27 September 2017	5.9	0.767	13.00
MEAN			12.12

Table 6. Measured solar PV yield on days without direct shading.

This indicates a mean conversion efficiency over the 9 days of 12.1%. The peak conversion efficiency of 13.4% can be compared with our original estimate of 14.5% for September (Table 5, page 73). The difference of 1.1% can be attributed to a combination of, in order of significance:

- Short-term direct shading events (tree branches) in the morning and afternoon, apparent in Figure 42;
- Changes in the sun's elevation angle during the day;

- Directionality of the silicon PV technology (not detailed in the solar panel data sheets); and
- Lower efficiency of the MPPT solar charge controller due to higher ambient conditions (remembering that its rated maximum efficiency is 98%).

These residual losses totalling 1.1% are relatively insignificant when compared with losses of up to 90% from partial direct shading and up to 13% due to increased temperature over STC.

For the purpose of future estimates of solar PV system yield based on BOM insolation data, a conversion efficiency of 12.1% for unshaded panels is a realistic figure for preliminary design purposes. This is for solar PV panels with a rated panel efficiency of 16.8%, implying a system conversion efficiency factor of 0.953 on the rated panel efficiency. The yield from unshaded solar PV panels in the subtropics can therefore be readily estimated from local daily insolation and temperature data.

5.6 Discussion

It is helpful to examine the relative significance of solar charger system losses using graphics. Figure 43 shows average solar PV system yield and system losses based on the findings from this project. The total area of each circle represents the average daily insolation (the 2016 average of BOM Maryborough station monthly average of BOM daily total solar exposure) on the PV panel area.

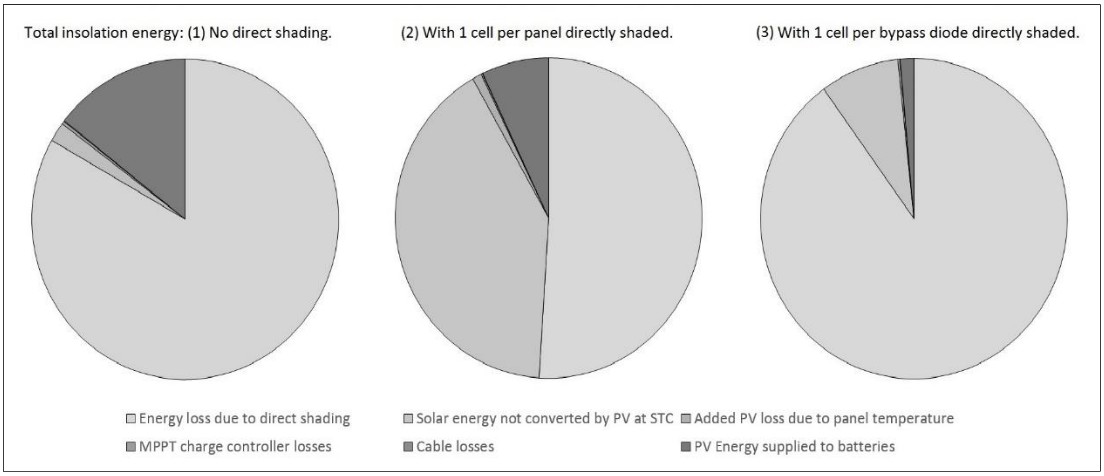

Figure 43. Solar PV system losses with increasing amounts of near-end direct shading.

Figure 43 shows PV system losses and yield for three cases of increased direct shading by near-end obstructions. Case (1) with no direct shading, has most energy loss resulting from the solar panel rated efficiency. Case (2) shows the effect of constant near-end shading of one PV cell per panel.

Case (3) shows the effect of more significant direct shading, such as from a 150mm mast or boom on a sailing vessel. When this shading effects at least one cell per bypass diode string, it will cause the yield to rapidly drop by 90%, as occurred on 5 October 2016 (Figure 30, page 74).

For the purpose of guiding future solar PV system designs it is worthwhile to understand the relative significance of the various system losses. Figure 44 has been developed based on case (2) with this goal in mind.

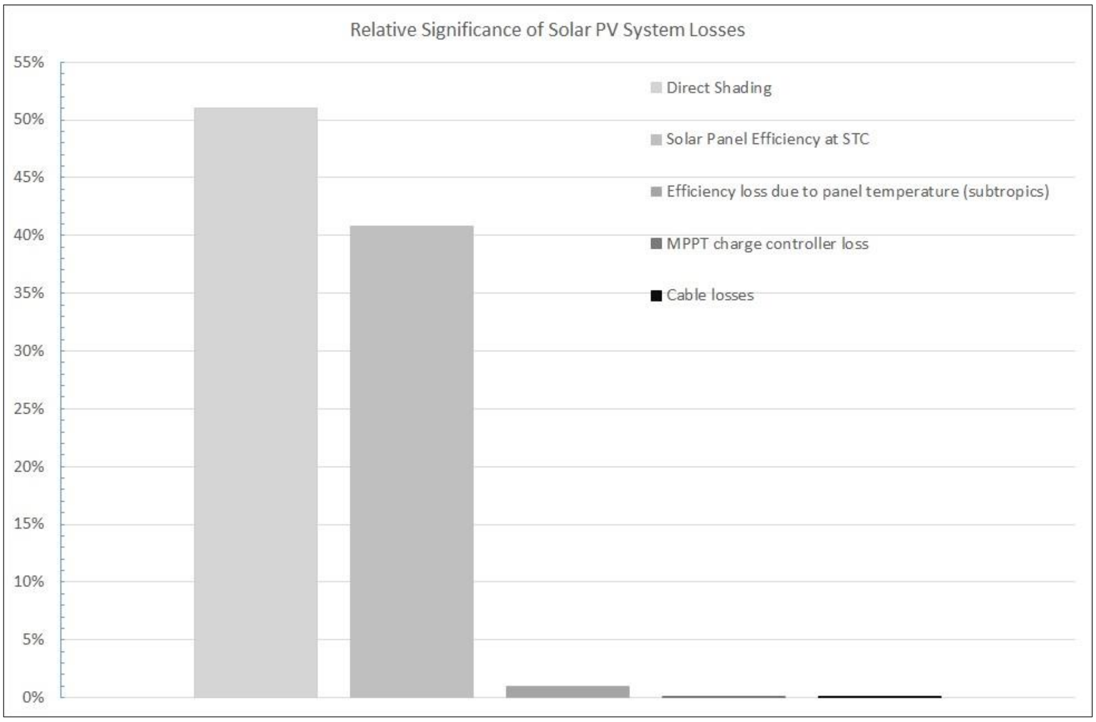

Figure 44. Relative significance of solar PV system losses.

Figure 44 indicates a hierarchy of system losses along the solar energy conversion chain, starting at the Sun:

1. Direct shading of the solar PV panels. Eliminating or reducing direct shading will provide the most significant improvement to solar PV yield. Design mitigation options include:
   a. careful location of panels relative to vessel superstructure,
   b. laying out panels and adding bypass diodes as described in Section 6.3.3,
   c. using MPPT solar charge controller/s.
2. Performance of the PV panel technology. Considerations include:
   a. PV technology efficiency,
   b. PV temperature effects. Panel cooling, at least via passive air circulation, should be considered in subtropical and tropical zones.
3. Internal PV system losses are of little significance:
   a. Commercialised MPPT solar charge controllers provide yield conversion improvements that dwarf their electronics losses.
   b. Cables that are appropriately sized for system current and voltage drop will have minimal effect on energy loss in a small vessel. Furthermore, the additional cost of using over-sized cables to increase system efficiency is generally not warranted for small and medium-sized vessels.

For the purpose of preliminary design and modelling of solar PV systems for Marine Electric Propulsion, only the most significant losses (direct shading, panel efficiency, panel/bypass diode layout and panel temperature) require close attention. Other system losses can then be assumed to approximate:

MPPT solar controller efficiency:		0.98	(98%)
Cable losses	*	0.994	(0.6%)
Residual system losses	*	0.989	(1.1%)

Balance of System (BOS) efficiency	=	0.963	(or 3.7% loss).

5.7 Summary of findings for design of Solar PV in MEP

Using MS Turanor PlanetSolar as a benchmark, a "Mean Feasible Power by Solar", or MFPS index has been derived for use in vessel preliminary design,

Equation 2: $$MFPS = \frac{0.1178 \times (L_{wl} \times B_{max})}{P_b}$$

The MFPS index can be used to calculate the realistic solar PV percentage contribution to a vessel's propulsion energy. Figure 24 provides a comparison of recent new build vessels using the MFPS index.

In order to improve understanding of solar PV system losses on a moving platform, a solar battery charger and reference PV cell were fitted to an operational locomotive. Using a shunting locomotive that remained within 3.5 km of two meteorological stations measuring insolation, rainfall and temperature provided an opportunity for data comparison and yield analysis that would not be possible on an ocean-going vessel. Typical PV system losses were found and can be incorporated and prioritised in the design of solar PV systems for marine vessels.

Near-end direct shading, of only one cell per bypass diode string, has a disproportionate effect (eg. 90% reduction) on solar PV yield. In a vessel with a substantial superstructure, or a sailing vessel with panels shaded directly by masts, booms and sails, the more bypass diodes per panel, the better. Investment in electronics topside (ie. increasing the number and location of bypass diodes in solar panels) is at least as important as investment in electronics below deck (ie. use of a MPPT solar charge controller).

The irradiance amplification effect of diffuse irradiance, including Fresnel (water) reflection has implications for the design of solar power systems for marine vessels. A dome topology (eg. the shape of a tree in an open field, Figure 34, page 79) will be more effective than a planar topology in capturing direct and diffuse irradiance, particularly on a vessel where there is constant movement due to waves and changes in heading. Solar PV technology types that optimise both direct and diffuse irradiance, will also be more effective. As solar PV prices reduce and PV coating options improve,[10] extensively covering vessel topsides with solar PV, in the form of Vessel Integrated Photovoltaics (VIPV), may become practical for improving yield.

During the design and modelling of solar PV sub-systems for Marine Electric Propulsion, the most significant losses require the closest attention. Reducing direct shading will have the most significant effect on solar PV yield. Direct shading can be mitigated during system design by (in priority order):

a. careful location of panels and vessel superstructure,
b. panel layout and additional bypass diodes as described in Section 5.5.3,
c. use of MPPT solar charge controllers.

Of secondary importance is PV panel technology selection, including PV technology efficiency, directionality and temperature sensitivity. Panel cooling, at least via air circulation, should be considered in subtropical and tropical zones.

Internal electrical system losses of the balance-of-system (i.e. excluding PV panels) has been found to be of little significance, because:

a. Commercialised MPPT solar charge controllers provide yield conversion efficiencies that dwarf their electronics losses.
b. Cables that are appropriately sized for system current and voltage drop will have minimal effect on energy loss in a small vessel. Furthermore, the additional cost of using over-sized cables to increase system efficiency is generally not warranted for small and medium-sized vessels.

The balance-of-system electrical losses can be approximated by a BOS efficiency of 0.963.

Monthly averages of daily insolation and maximum ambient temperature can be determined from meteorological sources such as the Australian Bureau of Meteorology (BOM) or weather satellite data and used to provide reliable estimates of solar PV system performance.

The design of the solar PV prototype included considerations to prevent moisture entry, as this will cause accelerated degradation of PV, electronics and connectors in any solar PV system. Solbian SP137 flexible solar panels are waterproof and used extensively in off-shore marine applications. The MPPT solar charger and other electronics were housed in an IP67 polymer equipment box. In the marine environment, the presence of salt mist and possibility of inundation mean that solar panels should be waterproof and electronics protected to at least IP54 as defined by IEC 60529 (dust protected, water splash from any direction has no harmful effect). For topside-mounted electronics, IP67 (immersion to 1m depth) and IP66 (powerful water jets) protection should be considered to prevent water entry from temporary immersion, green water and wave impact. For marine electronics housed in equipment areas away from heavy salt spray and not housed inside IP rated enclosures, conformal coating is suggested to prevent premature failure due to corrosion from salt-laden air.

Chapter 6: Conclusions

6.1 Summary of this project

This research project reviewed international progress in marine electrical and renewable energy systems research and development. It also identified and highlighted the market drivers for high-efficiency vessel development in Australia.

A software model for use in the preliminary design of marine electric propulsion systems was investigated. The model development commenced with an investigation of methods for approximating hull and propeller performance using minimal input parameters. The model was compared with a commercial spreadsheet and the measured performance of the first all-electric ferry to operate on the Swan River in Perth, Western Australia.

The application of solar photo-voltaic (PV) technology to marine propulsion was investigated, leading to derivation of an index for estimating a vessel's maximum feasible power by solar (MFPS). A solar PV battery charger was designed for a shunting locomotive, along with a reference PV cell and data logging equipment. Comparison of solar charger performance with meteorological data provided insights for improving the design of future marine solar PV installations.

6.2 Findings from the review of emerging MEP technologies

This project commenced with a systematic literature review of electrical technologies applicable to marine electric propulsion. Technologies were grouped, categorised and their relative technology maturity determined. Concept maps were then generated for each technology type and individual technologies shaded relative to technology maturity. This analysis (see Figures 2, 3, 4 and 6) highlighted significant emerging MEP technologies.

Energy storage is a key enabling technology for marine electric propulsion. It is currently "letting down the team" in terms of energy density and specific energy compared to diesel fuel. Nevertheless, the focus on this problem, especially in automotive applications and European vessels, is leading to improvements. Lithium-ion battery technologies have been successfully commercialised for on-board rechargeable electrical energy storage. Augmentation of the power density of energy storage systems with supercapacitors with very high power capabilities, will be useful in highly variable power and rapid charging applications.

The use of permanent magnets is now widespread in commercially-available marine electric propulsion motors. Permanent magnets are enabling novel motor topologies, which are providing improvements in torque/speed performance. IM motors are maintaining their prominent position in automotive applications. However, in the low-speed, high-torque region required for driving a propeller without a gearbox (<1500 RPM), permanent magnet synchronous motors (PMSMs) have higher efficiency than IM or SRM motors and will therefore be more useful in marine applications.

High-temperature superconductor (HTS) technology may be feasible in applications where the need for high power density, reduced machinery size and reduced mass out-weighs the added complexity of cryogenic cooling. The decreasing price of high-temperature superconducting wire may facilitate commercialisation of HTS motors for niche applications due to improving costs relative to copper wire.

The introduction of high power DC distribution systems in ships will facilitate the interfacing of increasingly diverse energy sources and loads. Solid state power conversion devices are available in wind turbine and rail traction applications that have ratings suitable for implementing high-power DC distribution in mid-sized vessels. Furthermore, the use of Silicon Carbide technology shows considerable promise for improving the efficiency of high-power DC distribution electronics in mid-sized vessels.

Significant improvements in solar PV module price and efficiency have made solar technology commercially feasible for on-board electricity generation, but solar energy's contribution is limited by solar irradiance and the vessel's catchment area. Nevertheless, the lack of use of solar PV in marine vessels is not consistent with its low cost and immense potential, as demonstrated by the circumnavigation by "MS Turanor PlanetSolar" in 2012 using only solar energy.

6.3 The significance of this project to Australian shipbuilding

Australia is in an important position globally with regard to the development and use of high-efficiency vessels and Marine Electric Propulsion. For example, as a remote and sparsely populated nation, the transport sector has disproportionate significance to Australian domestic and international trade. Australia is a leader in the commercial use of modern sailing technology and is the world leader in high-speed aluminium shipbuilding.

Efficiency improvement and emissions reduction initiatives world-wide are creating a significant opportunity for the sector. This research project reviewed international progress in marine electrical and renewable energy systems research and development. It also identified and highlighted significant market drivers for high-efficiency vessel development in Australia. However, the application of electrical and renewable-energy technologies in vessels built by Australian aluminium shipbuilders is at least six years behind their European counterparts.

Australia receives an abundance of solar energy. In particular, northern Australia lies within +/- 30^0 latitude of the Equator, where solar energy is most useful over the full year. This underlines the strong potential of solar PV for MEP applications in Australia. The potential is lacking only in development and action.

6.4 Findings from modelling for preliminary design

The development of a model for Marine Electric Propulsion commenced with the programming and analysis of vessel hull and propeller components. The Moody methodology was chosen for its basis in vessel preliminary design. The results from this model were compared with other models of the performance of the first all-electric ferry operating on the Swan River in Western Australia. It was found that, while the Moody methodology requires many more input parameters, it compares favourably to a commercial spreadsheet due to its ability to estimate propulsion power including parameters such as wind resistance, added resistance due to sea state, appendage resistance and hull fouling resistance.

While not essential for short-route river ferry applications, the additional input parameters would be relevant for applications where estimates of range and sea-state performance are required for ocean-going vessels. These are also important considerations for ensuring that an ocean-going vessel design will satisfy the IMO's Energy Efficiency Design Index (EEDI) for new ships and in particular, that the vessel will meet powering requirements for a Beaufort sea state of 6, as required by the IMO guidelines for calculating the coefficient f_w for the decrease in vessel speed in a representative sea condition (MEPC.1/Circ.796). [135]

6.5 Findings on Solar PV technology

The use of solar PV on vessels is constrained by the myth that it is only useful for providing auxiliary power on vessels. Using the "MS Turanor PlanetSolar" vessel as a benchmark, a "Mean Feasible Power by Solar", or MFPS index was derived for use in vessel preliminary design. The MFPS index provides a simple estimation of the realistic solar PV contribution to vessel propulsion energy.

A solar battery charger, reference PV cell and data logger were developed and installed on an operational locomotive in order to investigate the losses effecting solar PV yield.

Analysis of the solar charger data included comparison with calibrated meteorological data, including insolation, from the Australian Bureau of Meteorology (BOM). Comparison with reliable and calibrated meteorological measurements provided insights that would not be possible with an installation on an ocean-going vessel. The relative significance of losses in the solar energy conversion chain was determined to assist design and modelling of solar PV systems for marine vessels.

Near-end, direct shading of only one cell per bypass diode string, has a disproportionate effect (eg. 90% reduction) on solar PV yield. In a vessel with a substantial superstructure, or a sailing vessel with panels shaded directly by masts, booms and sails, careful panel layout is required. The more bypass diodes per panel, the better, to the extent that investment in bypass diodes will have a greater return than that of MPPT solar charge controllers – although investment in both is recommended.

The potential amplification effect of diffuse irradiance, for example from Fresnel (water) reflection has implications for the design of solar power systems for marine vessels. A dome topology will be more effective than a planar topology in its ability to capture direct and diffuse irradiance. As solar PV prices reduce and PV coating options improve,[10] extensively covering vessel topsides with solar PV, in the form of Vessel Integrated Photovoltaics (VIPV), may become practical.

For the purposes of design and modelling of solar PV systems for Marine Electric Propulsion, the most significant losses are direct shading, panel efficiency, panel/bypass diode layout, and panel temperature. Direct shading can be mitigated during system design by careful layout of panels and vessel superstructure, adding bypass diodes and using MPPT solar charge controllers. Compared to mitigation of direct shading, PV panel efficiency optimisation is of secondary importance. Panel cooling via air circulation, should be considered in subtropical and tropical zones. Internal electrical system losses in the balance-of-system (i.e. excluding PV panels) are of little significance.

In the marine environment, where meteorological stations are few and far between, the use of satellite insolation measurements over vessel routes should be considered. Using the findings from this thesis, daily insolation data could be adapted to solar PV system performance estimation and design optimisation.

6.6 Validation

These conclusions have been extensively validated during the project.

The epilogue to Chapter 2 (section 2.3) is the summary of a self-validation of the conclusions in the journal paper, "Emerging technologies in marine electric propulsion" and highlights changes in MEP technologies since the paper was published. Some of those changes verify projections and some modify the projections made in the original journal paper.

The journal paper, "Dawning of the age of high efficiency vessels" was comprehensively reviewed by a total of five reviewers and revised in response to their comments. It was initially reviewed by three reviewers and approved for publishing in Transport Engineering Australia, just prior to that journal ceasing publication. The paper was then reviewed by two further peer reviewers for the Australian Journal of Mechanical Engineering and revised before acceptance. The epilogue to Chapter 3 (section 3.2) highlights changes in market drivers and high-efficiency vessel development in Australia since the paper was published.

The early modelling work was validated using the "Ellie J" all-electric ferry, by comparing software model results against an Oceanvolt spreadsheet, Holtrop (MARIN) hull powering data calculated by Maxsurf Professional software and against the measured vessel performance.

The solar PV measurements logged during this project were compared against calibrated meteorology data from the Australian Bureau of Meteorology. Further validation was embedded in the solar PV system measurements by the use of a PV reference cell. This combination of data comparison and validation was important for determining the significance of energy losses along the solar energy conversion chain.

6.7 Further work

The preliminary design of a vessel with a traditional diesel propulsion power train is a complex task.[82, 83] With an electric or hybrid propulsion system, the complexity increases significantly with each additional energy source and energy storage sub-system. The need identified early in this project, for a holistic software model to assist in preliminary design of MEP systems, requires and is worthy of further development.

This project has closed the gap in understanding of Solar PV system performance, however the following sub-systems require further software modelling work towards the goal of a holistic MEP system model:

1. Batteries (including lithium-ion and lithium-sulfur)
2. Electric motors (including PM and high-temperature superconductor motors)
3. PEM and SOFC fuel cells

4. High power DC distribution
5. SiC power electronics.

Chapter 4, section 4.4 lists steps that should be considered for further development of vessel modelling software based on the Moody preliminary power prediction methodology.

Diffuse irradiation and the irradiance amplification effect of partial clouding has been described[140, 141] and modelled,[142, 143] however its consideration in the design and performance of marine vessel solar systems has been limited to date. Similarly, solar PV yield from irradiance reflected from the water's surface (Fresnel reflection) has been measured by Dammeier et al (2017)[144] for lakeside Building Integrated PV (BIPV). Their model of Fresnel irradiance as a percentage of total irradiance on a vertical surface shows a 5 to 15% contribution, depending on latitude. Importantly, in the context of this project's findings, irradiance amplification effects are high (closer to the sun) in the solar energy conversion chain. The effect of irradiance amplification on marine vessel PV systems is therefore worthy of further investigation, with a view to the eventual feasibility of Vessel Integrated Photovoltaics (VIPV) technologies.

The Australian shipbuilding industry has the potential to provide solutions of global significance in the areas of marine electric propulsion and emissions reduction. Further work in this area is paramount.

Appendix A : Comparison of powering performance models

The building and launch of the “Ellie J” electric ferry in 2015 provided real-world data for comparison of modelling software. Useful data was provided by the following vessel designers and builders:

- Derek Ellard of Scruffie Marine Pty Ltd,
- Claude Desjardins of Oceanvolt and
- Col Clifford of Compu-Craft Yacht Designs.

Derek Ellard provided the main vessel parameters and provided access to the vessel’s sister-ship to check hull parameters such as Length on Waterline (Lwl), Length between Perpendiculars (Lpp), propeller-to-hull clearance and Rudder Wetted Surface Area (WSA). The Little Perth Ferry parameters entered into the model via Power_exeGUI are shown in Figure 45.

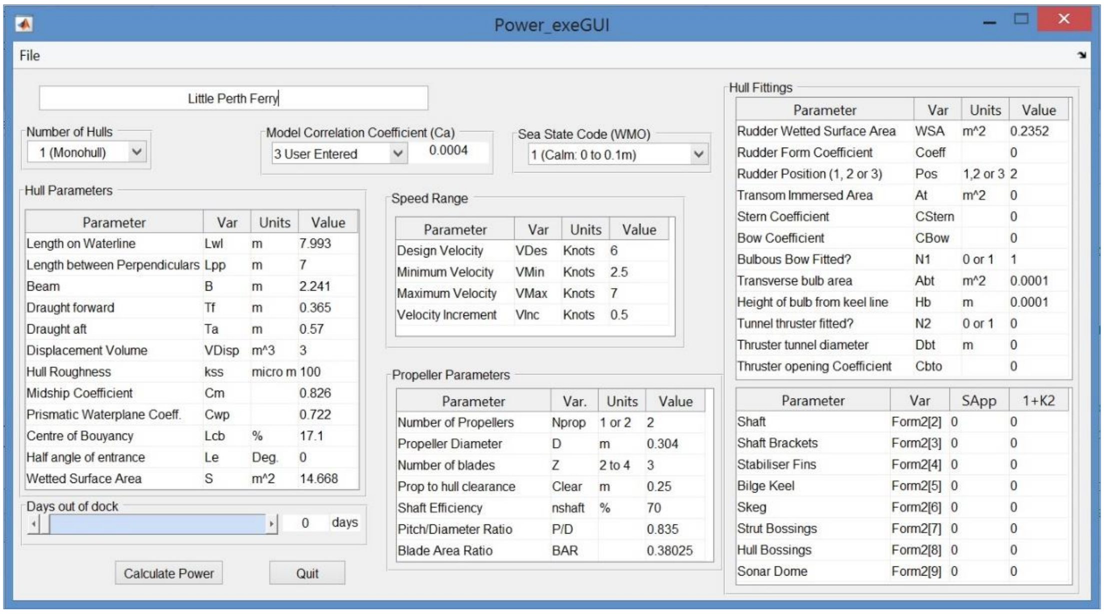

Figure 45. Little Perth Ferry "Ellie J" model parameters

Claude Desjardins supplied a propeller identical to the two propellers used on “Ellie J’, which enabled measurements of propeller diameter, P/D ratio and BAR.

Col Clifford supplied Holtrop (MARIN) hull powering data calculated by Maxsurf Professional software from the ferry’s lines. The Maxsurf Holtrop data was for smooth water only and didn’t include parameters such as propeller efficiency, wind and sea state. Because of this, the Maxsurf Holtrop plot should lie below the other estimates.

Claude Desjardins supplied the vessel powering data from “Ellie J” sea trials, which occurred on 21 Oct 2015, 16 Nov 2015, 18 Nov 2015 in Gold Coast, Queensland and on 29 May 2016 in Perth, Western Australia. The “Ellie J’s” outboard motor controllers don’t allow direct data download, so Claude Desjardins and Kevyn Townley, Managing Director of Little Ferry Co., photographed the screens for each data point, which we then transposed manually to Microsoft Excel, where the two electric outboard motor power measurements were summed and the two GPS-based speed measurements were averaged.

Claude Desjardins also supplied powering data generated by a commercial-in-confidence spreadsheet developed by Oceanvolt OY in Finland. The spreadsheet calculates powering requirement versus speed, based on only four parameters:

- Length on waterline (Lwl),
- Beam on waterline,
- Displacement and
- Hull format.

The spreadsheet was developed based on actual data accumulated by Oceanvolt from their experience with multiple electric vessel propulsion installations.

In summary, the power versus speed was obtained for “Ellie J” from:

5. Maxsurf Holtrop data,
6. Oceanvolt spreadsheet,
7. The model based on Moody’s estimates and
8. Actual vessel sea trial data.

These are plotted on the same axes in Figure 46.

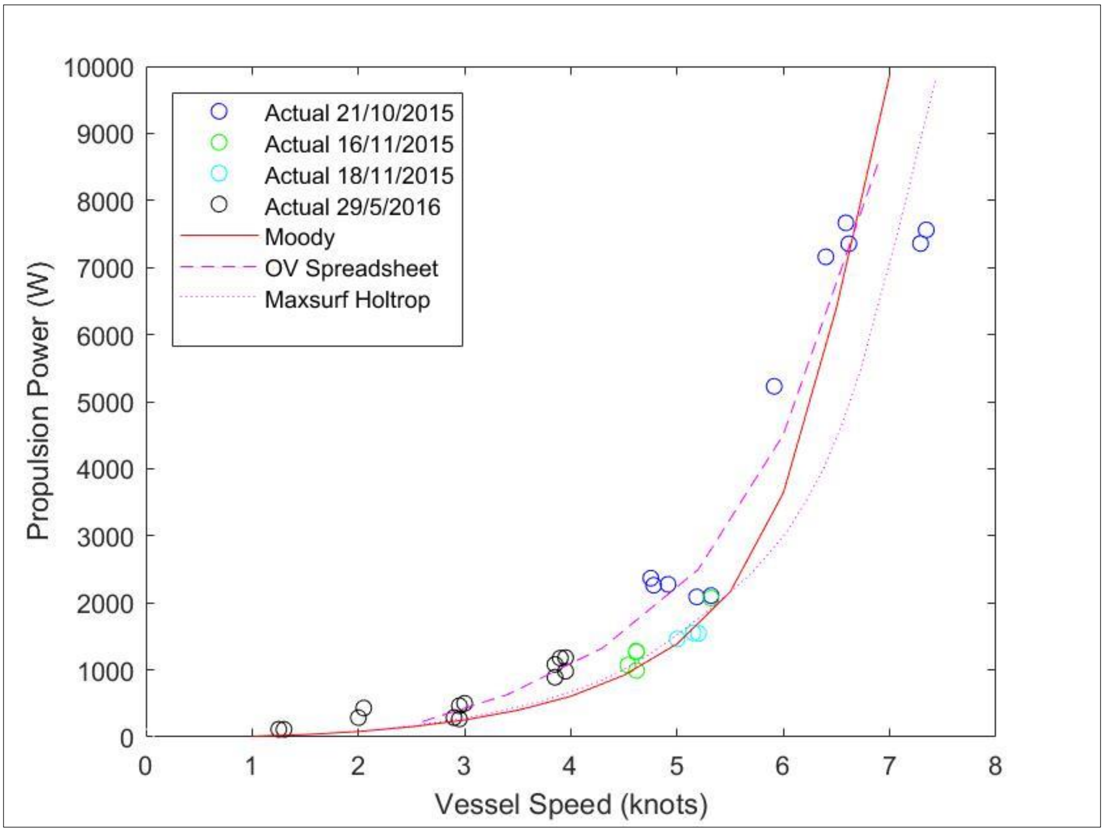

Figure 46. "Ellie J" modelled and actual powering performance.

The actual data shows some polarisation, which is expected with speed measured using GPS and affected by tidal currents and wind. The data shows an apparent +/- 0.5 knot variance, which is adequate for comparing preliminary design models.

All three models fit the measured data. As expected, the Maxsurf Holtrop data lies on the ‘optimistic’ edge (RHS) of the measured data, as it doesn’t consider propeller efficiency, wind, or sea state.

The Oceanvolt spreadsheet data lies on the more ‘realistic’ edge (LHS) of the actual data.

Two conclusions that can be drawn regarding the difference between the Moody model and the Oceanvolt spreadsheet:

3. The Moody model uses B-Series propeller data. The actual propeller efficiency could be better than B-Series at higher speeds, which would explain the Moody model slope being steeper above 6 Knots. With its strong basis in real-world data for similar-sized hulls and propellers, the Oceanvolt spreadsheet provides a better model than the Moody model for the case of calm water and no wind. As suggested in section 4.1, the choice of Wageningen B-screw Propeller Series rather than Gawn Series should be reviewed for Marine Electric Propulsion modelling, as Gawn Series

handle a larger P/B range and pitch diameter range than B-series and most propellers currently in use for electric propulsion have three blades.

4. 70% shaft efficiency was used for the Moody modelling, considering that each outboard motor consists of a pod-mounted motor and gearbox. The Oceanvolt spreadsheet calculates ‘Pbatt’, or power at the battery, which would include losses in the electric motor, gears and the power electronics.

The Oceanvolt spreadsheet closely approximates vessel performance, despite using only four input parameters. This compares with the Moody model requiring at least 25 input parameters for a calm sea estimate.

The comparison with “Ellie J” data highlighted several additional bugs in the original Pascal code, including input out-of-range and divide-by-zero errors. For example the software doesn’t accept a ‘zero’ bulbous bow, so this was approximated with a 0.0001 bulb area.

Appendix B: Bureau of Meteorology (BOM) data

B.1 Introduction

Australian Bureau of Meteorology (BOM) station location information[139] shows that there are two BOM weather stations in Maryborough, Queensland that measure daily solar exposure (insolation): station 040443 in the city and station 040126 at the airport. The Maryborough airport station 040126 measures solar exposure (insolation), temperature and rainfall data, while the city station 040433 measures only insolation. The Maryborough city station (040443 at 25°32'28"S, 152°42'20"E)[146] is less than 1km and the Maryborough airport station (040126 at 25°30'48"S, 152°42'55"E)[147] is less than 3.5km from the Downer Maryborough facility where the DH73 locomotive operates. This means that accurate daily BOM insolation, temperature, wind speed and rainfall data is available free, without the equipment, risks and expense of attempting to duplicate these weather measurements at the Downer Maryborough site.

Sufficient data was logged by the locomotive solar charger in 2016 and 2017 to identify and quantify the losses effecting its yield. Quantifying these losses and being able to correlate this with nearby BOM weather stations provides a sound basis for development of a methodology for adapting BOM data to estimates of real world PV power contribution for future rail and marine applications of solar PV systems.

In July 2016 the locomotive was parked where it was partially shaded by an awning (see Figure 25, page 67), so there are additional energy losses compared with the daily insolation measured by the nearby BOM weather stations.

B.2 Comparing two meteorology stations 320 km apart

While the Maryborough BOM weather stations provide daily aggregated insolation energy data, there are 29 BOM stations across Australia that log insolation every minute. The nearest one-minute station to Maryborough is in Rockhampton, approximately 320 km away, as shown in the BOM map reproduced in Figure 47.

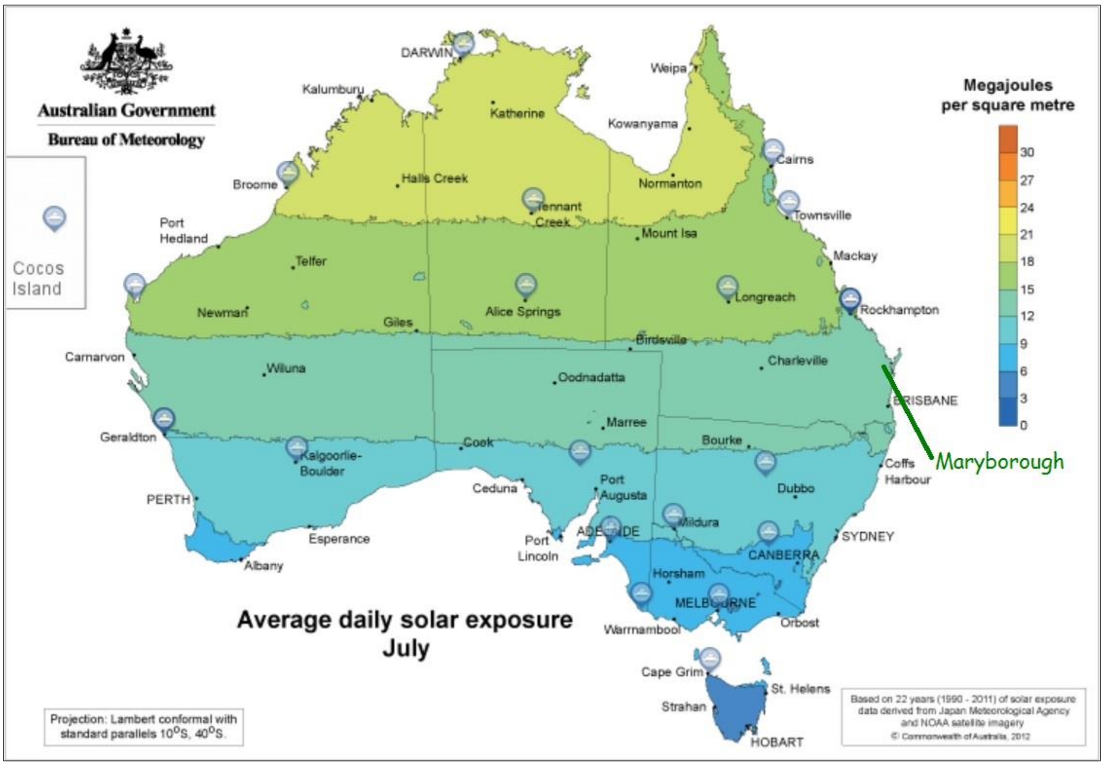

Figure 47. BOM one-minute solar data stations and July average daily solar exposure (insolation).[139]

The map reproduced in Figure 47 shows a strong correlation between latitude and average daily solar exposure during July. It was therefore reasoned that the BOM one-minute insolation data for Rockhampton and the BOM daily insolation data for Maryborough might be correlated and used to derive an index for estimating Maryborough one-minute insolation. To check this, the Rockhampton one-minute and Maryborough daily insolation data for July - August 2016 was compared using Figure 48.

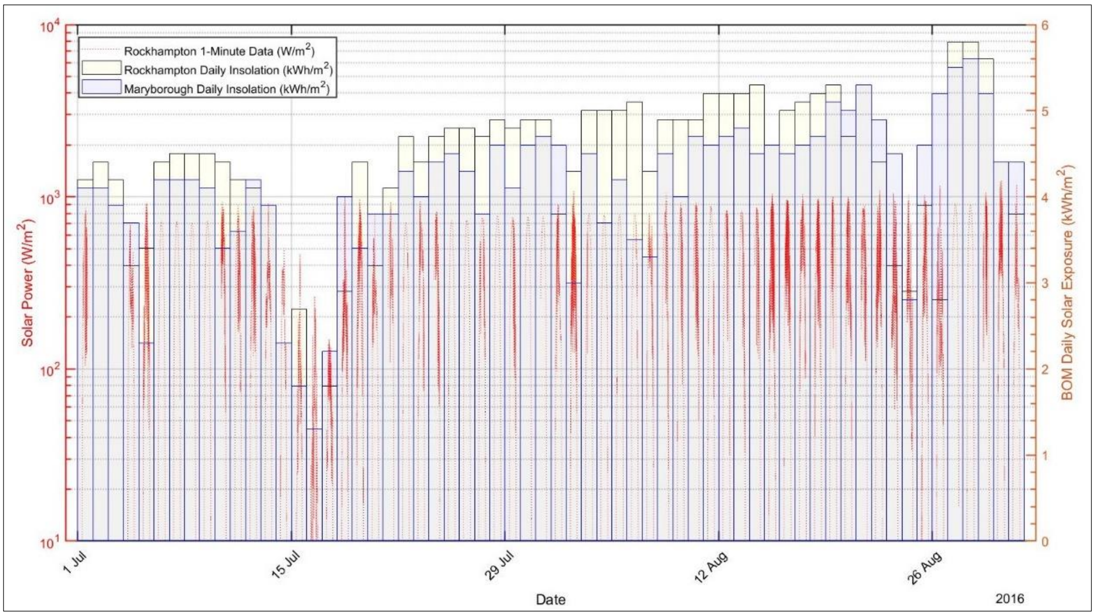

Figure 48. Rockhampton vs Maryborough BOM insolation data, Jul - Aug 2016.[139]

Figure 48 shows that Rockhampton daily insolation levels are generally higher than for Maryborough, as expected from the map in Figure 47. However, there is little correlation in daily variance. If an index were to be estimated, it could be in error by up to 2 kWh/m^2 (approximately +/- 45%) on any given day. An even greater error could occur in any given minute, due to local atmospheric and weather variances. This shows that it is definitely not feasible to correlate daily - let alone one-minute - solar energy at sites 320km apart. It also validates the concern that solar PV energy yield comparison with calibrated meteorological data would not be possible on an ocean-going vessel.

B.3 Correlating two meteorology stations 3.5 km apart

The Maryborough city BOM station (040443) and the Maryborough airport BOM station (040126) are less than 3.5km apart. The daily insolation data for these two stations was compared. Insolation data for both stations in July and August 2016 is shown in Figure 49, along with the inter-station difference on each day. This shows good correlation in daily insolation, with the difference (RHS axis) being at most 0.5 kWh/m^2 (< +/- 8%) on any given day. Since the two BOM stations are close, atmospheric and weather effects will be similar, so the most significant effect on any given day will be due to differences in direct (near-field) shading obstructions.

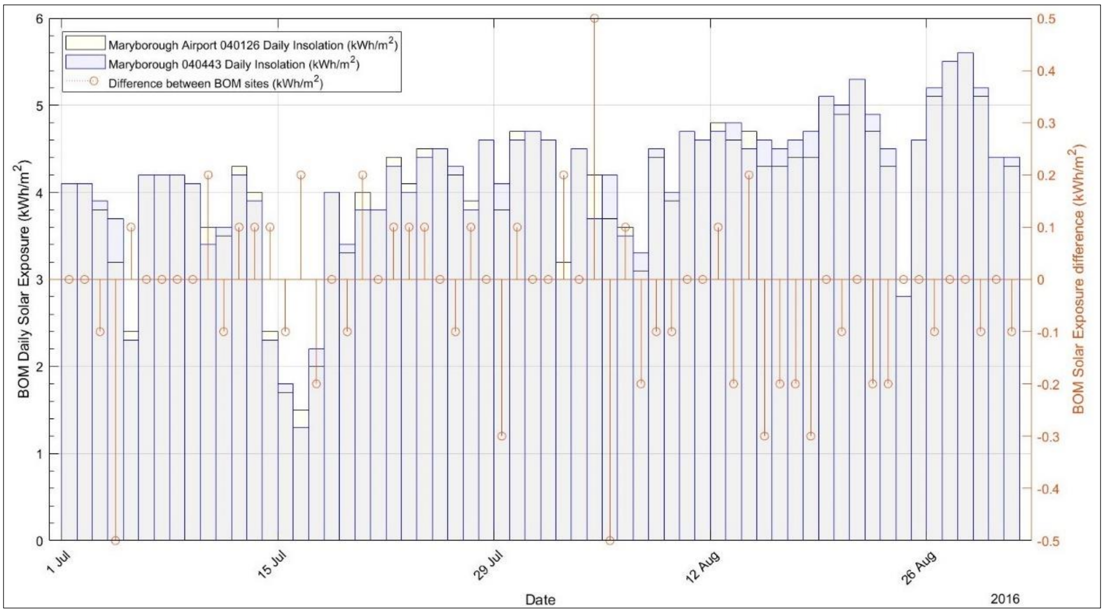

Figure 49. Maryborough city vs Maryborough airport BOM insolation data Jul - Aug 2016.[139]

The BOM skyline survey diagram for the Maryborough airport station (040126) is included in published metadata[147] and is reproduced in Figure 50.

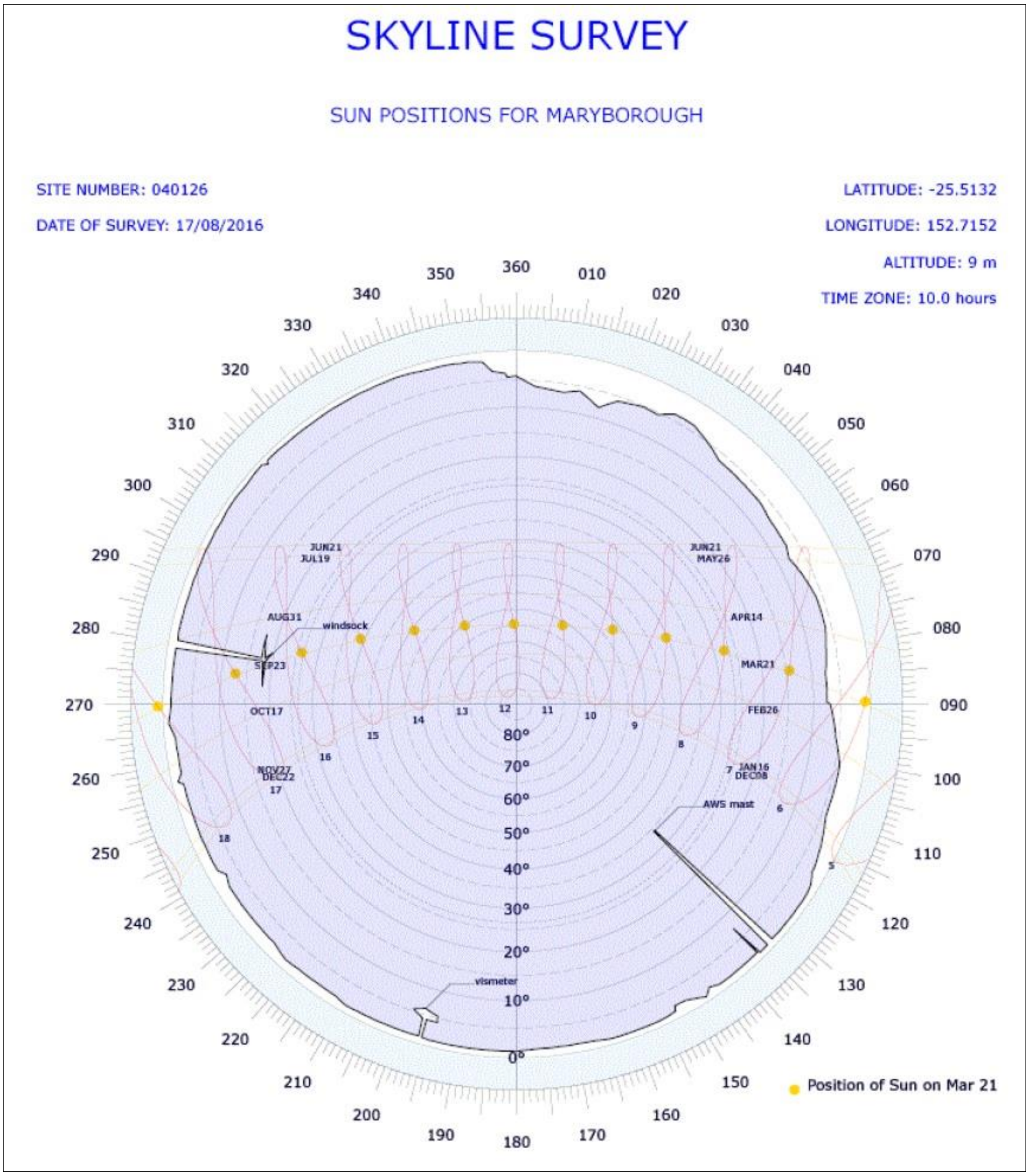

Figure 50. BOM skyline survey diagram for Maryborough airport station (040126).[147]

This shows the location of shading obstructions relative to Maryborough airport station (040126), for example:

- The airport windsock will obstruct direct irradiation at around 4:30pm in September and March each year.
- The tree-line to the north-east of the station will obstruct direct irradiation until around 7am in winter months.

Unfortunately a BOM skyline diagram for the Maryborough city station (040443) is not included in its published metadata.[146]

The Maryborough city BOM station (040433) is closest to the Downer facility where the shunting locomotive operates. However city BOM station 040433 data would only be more representative than airport station 020126 data if daily-averaged differences in atmospheric and weather conditions over a distance of 3.5km were significant. Based on Figure 49, the daily-averaged differences in insolation are insignificant.

Based on this information and analysis, it was determined that using the highest level out of the two insolation levels measured at Maryborough airport station (040126) and Maryborough city BOM station (040433) on each day would reduce the effect of near-end shading obstructions from the BOM insolation data. This calculation was included programmatically in the Matlab analysis.

B.4 Effect of diffuse irradiance on solar PV yield

An interesting phenomenon is apparent in the BOM Rockhampton one-minute insolation data shown in Figure 48 (dotted red plot). On partially cloudy days, such as 10 – 13 July 2016, the peak solar insolation levels are higher than on adjacent clear sunny days, such as 6 – 9 July 2016. The BOM Rockhampton one-minute insolation data is described by the BOM[148] as "global solar irradiance" and is the summation of two components:

1. Direct solar irradiance, the solar power arriving at the Earth's surface from the Sun's direct beam, is measured by a pyrheliometer with 5° field-of-view mounted on a solar tracker and
2. Diffuse solar irradiance, measured by a pyranometer, typically with dual glass domes shaded from the Sun's direct beam by a shading disc attached to a solar tracker. The angle subtended by the shading disc is equal to the 5° field of view of the pyrheliometer.

This means that the one-minute insolation (global solar irradiance) data has less directional bias than a flat solar PV cell.

On partially cloudy days, during breaks in the cloud cover (eg. Figure 34, page 79), the combination of direct solar irradiance and irradiance reflected off clouds causes peaks in global irradiance that exceeds the peak level on clear sunny days. This irradiance amplification effect of partial clouding can be seen more clearly in Figure 51, which zooms into the Rockhampton BOM data[139] for the period 6 – 13 July. This is plotted against a LHS y-axis with a standard used scale in Figure 51, rather than the logarithmic scale used in Figure 48.

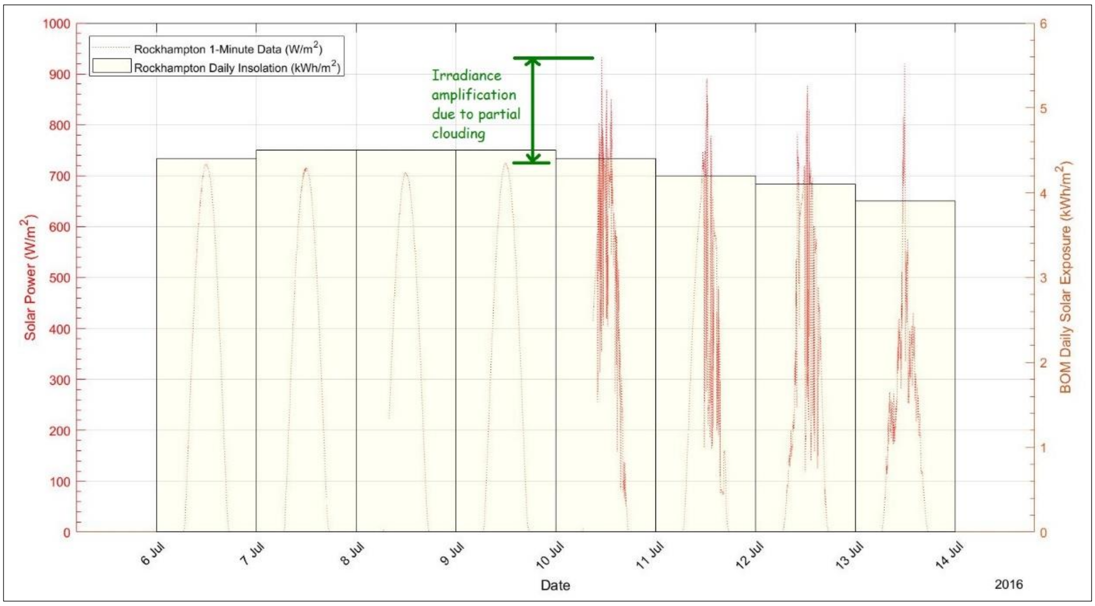

Figure 51. Rockhampton BOM daily and one-minute insolation data, 6 - 13 July 2016.

Figure 51 shows that on 10 July 2016 in Rockhampton, the amplification effect of reflection from clouds during partial clouding amplified one-minute insolation power levels by up to 28%. Section 1.2.3 of "Planning and Installing Photovoltaic Systems"[21] explains that yield from diffuse irradiation is also important at 52.5° latitude in Berlin, Germany during winter.[21]

Diffuse irradiation and the irradiance amplification effect of partial clouding has been described[140, 141] and modelled,[142, 143] however its consideration in the design of marine vessel solar systems has been limited to date.

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